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Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain

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Abstract

Arid lands are characterised by a combination of high temporal variability of rainfall and spatial heterogeneity of soil surface properties. In response to these environmental conditions, sources and sinks of runoff water and sediments tend to be organised in mosaics with distinct spatial attributes. These patterns can be identified at several scales, each with a predominance of a different set of processes. The dynamic relationships between these patterns and processes are an essential aspect of spatial connectivity in arid landscapes. During the last six years, part of the research at Rambla Honda, a field site in Southeast Spain operating under the MEDALUS project, has been concerned with this subject. This paper reviews the results obtained up to date at the patch and the hillslope scales. The research at the patch scale focused on the role of vegetation as a source of spatial heterogeneity that affects short-range redistribution patterns of water and sediments. The approach has been to identify the dynamic relationships between plant clumps and bare ground in sparse vegetation mosaics, using field observations, experiments and simulation models. Field observations included runoff and sediment yield measurements on bounded plots and hillslope sectors, analysis of spatial correlation structures, as well as physiological and architectural properties of plant functional types. Experiments included rainfall simulation and runoff exclusion in the field, and soil fertility bioassays both in the field and the laboratory. A cellular automata model was built to explore the interactions between plant clumps and sediment movement. The research at the hillslope scale was concerned with the long-range transference of water and sediments from rocky upperslopes to their footslope sediment fill. The approach was based on an analysis of the available information about spatial patterns of soil moisture and discharge of runoff and sediments from plots and stream gauges in a first order catchment. Results show that, at the patch scale, in sparse vegetation, a range of positive feedback mechanisms lead to nucleation, or to the increase of spatial heterogeneity, by concentrating resources in the soil beneath plant clumps at the expense of the neighbouring bare ground. This spatial heterogeneity arises dynamically through the interaction between plant growth and hillslope fluxes of water and sediments. Within specific boundary conditions, this interaction is 'tuned' towards the formation of mosaics of bare and vegetated patches with patterns that minimise redistribution lengths of water and sediments. The boundary conditions that affect the 'tuning' process include factors that determine the potential distance and transport capacity of runoff, such as temporal variability of rainfall, slope angle, slope length, among others, and plant specific factors that affect the efficiency of plant clumps in trapping the

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resources that are redistributed on the hillslope. At the hillslope scale, the transference of sediment and water between hillslope elements requires very specific within-event temporal distributions of rainfall that allow for the widespread formation of a saturated layer at shallow depth and overland flow to reach first order channels. During most rainfall events these conditions are not met and, therefore, in most seasons, mean values of soil moisture do not increase downhill, and rather reflect variation in local soil properties than the effects of lateral redistribution processes. As a consequence, it may be expected that small changes of the frequency distribution of rainfall characteristics, in terms of within-storm temporal distribution of intensities, could lead to significant changes in soil moisture patterns and hydrologic connectivity between hillslope elements.

Keywords: erosion; infiltration; runoff; sediment yield; semi-arid environment; Spain; vegetation

1. Introduction

Soil water not only moves up and down through the profile by percolation and evaporation, but also laterally between different parts of the landscape through surface and subsurface flow. Likewise, sediments not only accumulate on-site as a result of weathering and soil formation, but are also reallocated, by water, wind or gravity.

These redistribution processes underlie many of the structural and functional characteristics of the landscape. They determine the spatial distribution of sources and sinks of water, transported solutes and sediments. In this way, redistribution influences the spatial patterns, not only of soil, vegetation and ecosystem properties (Gonzalez Bernaldez, 1981; Falkenmark, 1990; Stafford Smith and Pickup, 1993), but also of hydrological and erosion-sedimentation systems (Pickup, 1985).

Compared to humid environments, where redistribution of water and sediments occurs mostly as subsurface flow and mass movement (Kirkby and Chorley, 1967; Kirkby, 1989), redistribution is largely driven by overland flow and surface wash in drylands (Yair and Lavee, 1985; Abrahams et al., 1991). Moreover, the high spatial and temporal variability of rainfall is characteristic of dryland climates (Slatyer and Mabbutt, 1964), and as a consequence, in these regions, most of the geomorphic work is performed during extreme events (Thornes and Gilman, 1983; Kirkby, 1989; Cooke et al., 1993). In addition, the high spatial heterogeneity of land surface conditions, in terms of infiltrability, sediment availability and roughness is also a common feature of drylands (Yair and Klein, 1973; Thornes et al., 1990; Parsons et al., 1992; Cooke et al., 1993).

The combination of high spatial variability in rainfall and local differences in land surface conditions, contribute to a much more intricate patchwork of sources and sinks in drylands than in humid landscapes. In drylands, patches of land may remain isolated in terms of the lateral exchange of water and sediments, forming cells that are relatively disconnected from neighbouring areas (Pickup and Chewings, 1986).

Water and sediment exchange between sources and sinks occurs at several spatial scales, each of which being characterised by a different set of processes. At the patch scale, which is relevant in interfluve areas, the vegetation is an important factor in creating spatial heterogeneity (Schlesinger et al., 1990; Abrahams et al., 1995), which determines for example the location of infiltration and sedimentation sites (Puigdefabregas and Sanchez, 1996). At the hillslope scale, sources and sinks are often connected through first order channels and their spatial distribution is rather controlled by topographic and lithologic factors (Yair and Lavee, 1985).

The research carried out at the Rambla Honda field site over the last six years has been concerned with these topics. A range of specific studies in soil processes, vegetation dynamics and hillslope hydrology have been conducted, yielding a body of information that is now available.

The objective of this paper is to review the results obtained up to date, and to identify the main trends and regularities. In so doing we will focus on the processes that drive the spatial redistribution of water and sediments at the patch and the hillslope scales.

At the patch scale, particular attention will be paid to the role of vegetation in creating spatial heterogeneity, and its implications for water and sediment redistribution in interfluve areas. At the hillslope scale, the work will focus on the factors that determine the transfer processes of matter between hillslope elements, and their effect on the spatial distribution of soil moisture.

2. The Rambla Honda field site

2.1. Geographical setting

The Rambla Honda (Fig. 1) is an ephemeral river (*rambla*) draining an area of 30.6 km^2 in the southern slope of the Sierra de los Filabres, a mountain range consisting mainly of Pre-Cambrian to Triassic metamorphic rocks. The river ends at the Honda fan, which is the backfilled portion of a coalescent mountain front fan complex which has developed since the Late Pliocene, overlying the Neogene depression of Sorbas–Tabernas (Harvey, 1987) in the eastern part of the Betic Cordillera, in southeast Spain.

The rock type of the area consists of a monotonous and thick series of highly fractured, dark grey, fine grained, slaty micaschists from the Devonian–Carboniferous. Neotectonics have affected the previously fractured series with new fractures and folds of very large radius. From the Tortonian to the Early Pleistocene, a distension phase was followed by a compressive phase which is still active (Montenat et al., 1987).

The degree of weathering of the bedrock is related to the lamination layering pattern and to the proportions of garnets and quartz. When the latter is large, spurs and shoulders are formed by differential erosion and colluvial debris are accumulated uphill behind them.

In the middle to lower part of the hillslopes, the slope deposits grade into an alluvial fan formation that is connected to the large Rambla Honda fan system. The tributary fans are made up of imbricated gravels, as well as lenses of cross-bedded sand-supported gravels, indicating a debris flow regime, that probably operated under more humid climate conditions in the Late Pleistocene (Harvey, 1987). The

Fig. 1. An oblique view of the lower sector of Rambla Honda. The field site is installed in the hillslope on the right-hand side. (Photo Chadwick).

depositional sequence shows no major break in sedimentation and little or no cementation. Fan distribution within the main valley is essentially controlled by neotectonics (Delgado, 1995). Fan bodies are being dissected by the present drainage network and the headward areas have mostly been eroded. Pre-Würm phases of predominant aggradation, followed by post-Würm dissection phases, have been described in the area as a long term Quaternary trend of sediment stock diminution (Harvey, 1984).

2.2. The field site

The field site is located in the lower section of the Rambla Honda (UTM 30S-WG-5509). It was installed in 1991, within the framework of the MEDALUS project (Brandt and Thornes, 1996), and later became also a research facility for a range of other projects. A full site description is provided in (Puigdefabregas et al., 1996). The climate is semi-arid, with a mean annual temperature of 16°C and mean annual rainfall of approximately 300 mm, which is concentrated in the winter season. Maximum rainfall intensity (I_{30}) during the period 1989–1997 was 32.5 mm h^{-1}. The area is characterised by a catenal sequence of soils and vegetation. In the upper hillslope sectors, there are *Typic Torriorthent* soils and *Stipa tenacissima* tussocks on micaschist bedrock. In the alluvial fan sectors, *Typic Torrifluvents* soils are found, with *Anthyllis cytisoides* shrubs and *Retama sphaerocarpa* bushes, in their upper and lower sectors respectively. The outlying parts of alluvial fans grade into fluvial terraces which exhibit a clear stratification and an irregular distribution of organic matter down the profile.

On the upper hillslopes, *S. tenacissima* used to be harvested for cellulose, while the footslope sedimentary fill was cultivated with rainfed cereal crops. Both types of land use ceased about 35 years ago.

2.3. Field observation layout

An east-facing hillslope sector of 18 ha with a median slope angle of 22° was selected for setting up observation protocols and field equipment (Fig. 2). The study area stretches from the valley floor, at 630 m altitude, to the water divide at 800 m. Grazing has been excluded from the area since September 1991. The basic long term observation system (Puigdefabregas et al., 1996) consists of the following:

(a) Nine measurement areas (MA) of 500 m^2–1000 m^2, three in each vegetation type along the catena. In each MA, measurements were made of basic soil properties, soil moisture, runoff and sediment yield, as well as plant biomass balances.

(b) Two stream gauging systems (H flumes) installed along a first-order channel draining the hillslope down to the valley floor. One of the flumes (F3) is located in the upper and rocky hillslope sector and drains an area of 0.29 ha. The second flume (F1) is installed in the lower hillslope, where the channel dissects the sediment fill, and drains an area of 4.65 ha.

(c) Four bore holes were drilled along a transect, from the apex of the alluvial fan to the valley floor, to investigate the sedimentary characteristics of alluvia and colluvia and to monitor changes in the water table height. The boreholes reached the underlying micaschist bedrock. The thickness of the sediment deposits, in a downslope direction was 18 m, 8 m, 16 m, and 28 m, the latter in the valley floor. The second bore hole was located in the gauged channel upstream of the flume F1.

(d) Meteorological information is provided by a base weather station and a set of rain gauges distributed across the area.

(e) The data obtained in the field by the different sensors are centralised and transmitted in real time to the EEZA headquarters in Almeria using a low-speed digital radio network (LAN) field facility, consisting of several microprocessor stations, based on Motorola MC68HC05/11 microcomputer families, and a central unit connected to a PC.

Runoff and sediment yield were measured in 2 runoff plots (2 m × 10 m) in each MA, for each rainfall event. Soil moisture was measured gravimetrically at increasing time intervals after each rainfall event. Two MA, one in *Retama* and another in *Stipa* stands were provided with recording systems for runoff, soil moisture, soil temperature and soil electrical conductivity. Details of these installations and procedures are described in Vidal (1994) and Puigdefabregas et al. (1996).

Two hillslopes with north- and south-facing aspects, slope angles of 18° and 24°, and slope lengths of 65 m and 55 m respectively, were also monitored

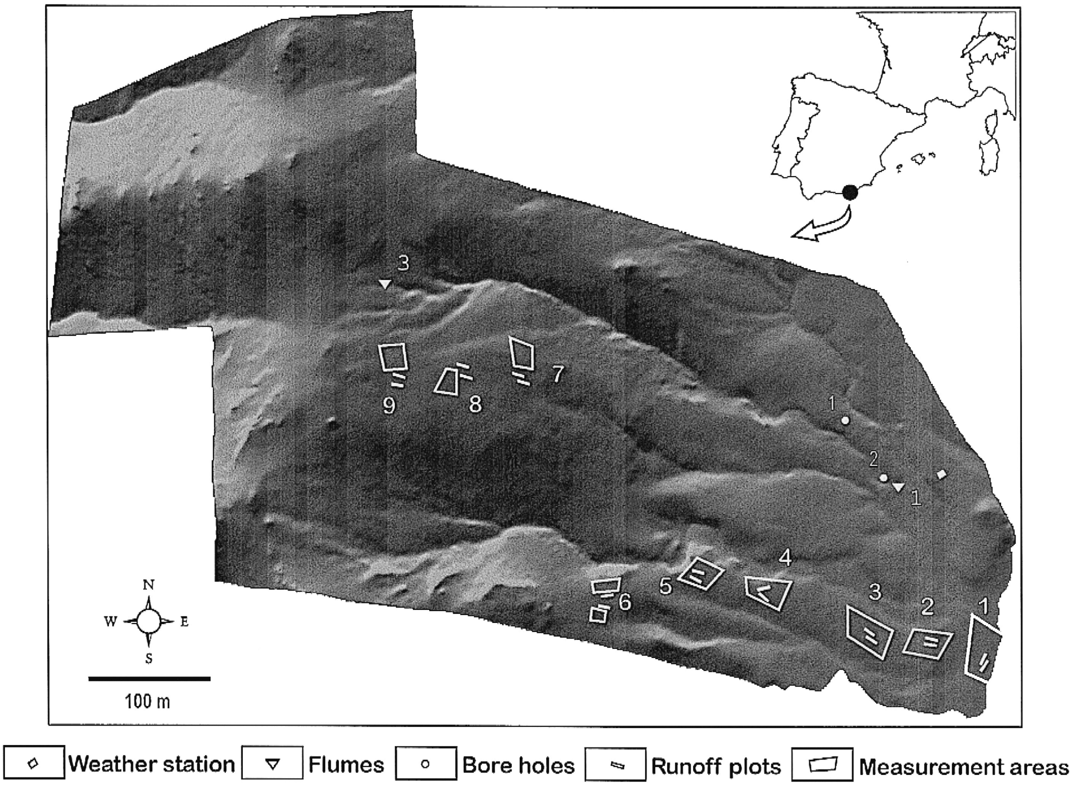

Fig. 2. Experimental layout at the Rambla Honda field site. Source: (Puigdefabregas et al., 1998).

for runoff and sediment yield from November 1990 to November 1992 (Sanchez, 1995). Both hillslopes are covered with colluvium (30 cm–50 cm depth) and a vegetation consisting of *Stipa tenacissima* grassland. On each of the two hillslopes, two rows of runoff collecting troughs were installed up at different slope lengths (17 m, 60 m on the north-facing slope, and 23 m, 49 m on the south-facing hillslope). In each row, 12 troughs of 0.5 m long were located at random.

Besides this basic field equipment layout, specific instruments linked to the ongoing research activities were temporarily installed. Instruments related to the topics of this review, included micro-meteorological (Bowen Ratio and Eddy Correlation) and neutron probe equipment for the study of evapotranspiration and soil moisture dynamics in sparse vegetation.

2.4. Relevant soil and vegetation characteristics

All of the soils in the area show little development of pedogenetic horizons, and are mostly channery loamy sands and channery fine sandy loams (with low proportions of silt + clay) (Puigdefabregas et al., 1996). Table 1 summarises their main characteristics. Coarse rock fragments, larger than 2 mm, within the soil mass, range from 15% in the lower part of the alluvial fan to 70% in the upper hillslope sector, with 2 mm–8 mm fragments being the most abundant size.

The soils on the alluvial fan contain less clay than those on the upper hillslope. Infiltration rates, determined by means of a simulated rainfall experiment at 50 mm h^{-1} (Nicolau et al., 1996) are high in the lower fan sector (20–40 mm h^{-1}), intermediate in the upper fan sector (9–25 mm h^{-1}) and quite low in the upper hillslope (3–8 mm h^{-1}).

The pH of the soil ranges from slightly acid (pH = 6.5) to moderately alkaline (pH = 8). The electrical conductivity is very low (0.003–0.022 S m^{-1}). The organic matter content ranges from 1.4%–4.7% in the lower fan sector to 2%–6.5% in the upper hillslope. The cation exchange capacity is

Table 1
Soil properties at the measurement areas along the Rambla Honda catena

MA no.	Depth (cm)	Crust cover (%)	RF > 2 cover (%)	O.M. (%)	Grain size (%)			TPV (vol/vol)	FC (vol/vol)
					> 2 mm	Silt	Clay		
1	0–5	15	15	1.6	13	21	4	0.34	0.16
	5–20			1.2	32	13	3	0.25	0.07
2	0–5	0	49	1.4	23	15	3	0.30	0.12
	5–20			0.7	39	12	3	0.32	0.08
3	0–5	0	61	1.4	41	13	3	0.29	0.12
	5–20			0.9	36	13	2	0.33	0.08
4	0–5	5	76	1.8	40	18	5	0.25	0.09
	5–20			0.8	36	23	4	0.29	0.09
5	0–5	2	60	2.6	41	16	4	0.23	0.08
	5–20			1.4	34	17	5	0.28	0.09
6	0–5	5	74	1.8	60	22	4	0.30	0.12
	5–20			1.3	41	24	4	0.35	0.09
7	0–5	13	75	5.2	56	25	7	0.36	0.16
	5–20			1.9	58	26	8	0.34	0.13
8	0–5	12	56	4.8	47	24	8	0.30	0.13
	5–20			2.4	67	30	10	0.32	0.12
9	0–5	4	73	3.8	55	22	3	0.34	0.15
	5–20			1.7	29	38	7	0.36	0.13

Weighed averages for plant cover over bulk soil values (including rock fragments). O.M.: organic matter; TPV: total pore volume; FC: field capacity; RF > 2: rock fragments > 2 mm at the soil surface; silt and clay: percentage over the fraction < 2 mm. MA1 to MA5, alluvial fan; MA6 to MA9, rocky upper hillslope. Source: (Puigdefabregas et al., 1998) (Copyright required).

also very low, less than 10 cmol kg^{-1}, as a consequence of the relatively low content of both clay and organic matter.

The sedimentary fill contains alternating beds of coarse and fine material. Gravels and sands, with a planar geometry, prevail in the upper profile section, whereas reddish–brown loams with small sandy intercalations predominate in the lower section, the intermediate zone shows transitional characteristics. Permeability estimates, obtained by constant head Lefranc type test in dry conditions, range from 8×10^{-3} cm s^{-1} for the total column to 2×10^{-2} cm s^{-1} for the gravel beds. Owing to the uncertainty associated to the outcomes of this test, these values should be interpreted with caution, but they suggest a moderate total permeability which almost doubles in the coarser layers.

Above ground biomass of perennial plants ranges from 100 g m^{-2} to 150 g m^{-2}, in the fan sector, and from 350 g m^{-2} to 450 g m^{-2} in the *Stipa* stands of the upper hillslope (Puigdefabregas et al., 1996). Annual plant biomass is highly variable in time and space, but in general, it increases in a downslope direction (9 g m^{-2} in the upper hillslope, 48 g m^{-2} in the upper fan, and 80 g m^{-2} in the lower fan sector). Perennial plant cover ranges from 20% to 40% in the entire study area.

3. Vegetation as a source of dynamic spatial heterogeneity at the patch scale

Natural vegetation in water-limited environments tends to adapt the density of its canopy in such a way that maximum growth is combined with minimum water demand stress (Eagleson, 1982). Key factors controlling this optimisation process are the evaporative power of the atmosphere and soil water availability (Woodward, 1987; Specht and Specht, 1989). However, a given canopy density in equilibrium with local soil and climate conditions, can be distributed according to different spatial patterns, forming mosaics of vegetated patches and bare areas of different sizes and shapes. Differences in soil properties between plant clumps and clearings have been widely described in the literature as reviewed in Schlesinger et al. (1990) and Puigdefabregas and Sanchez (1996). Most studies report a greater water storage capacity and a higher fertility in the vegetated clumps.

Two kinds of factors have been claimed as drivers of this spatial heterogeneity, differential erosion (Rostagno and Del Valle, 1988) and the trapping of resources by vegetated clumps, whether the resources be water (Rostagno and Del Valle, 1988), sediments (Rostagno and Del Valle, 1988; Parsons et al., 1992) or nutrients (Schlesinger et al., 1990). In mosaics driven by differential erosion, plant cover plays a passive role, there is less overland flow and soil erosion underneath plant clumps than in adjacent bare patches. Vegetated mounds arise, therefore, as a relict feature. In contrast, soil changes in mosaics resulting from the trapping of resources depend on canopy size and, therefore, reinforce themselves as the plant clump grows. This kind of mosaics result from a ‘‘nucleation’’ process, where vegetated patches become hot spots of soil and vegetation change. Research in Rambla Honda is particularly concerned with the dynamics of this nucleation process and with the relations between vegetated and bare patches.

3.1. Feedback mechanisms underlying nucleation

At Rambla Honda, three kinds of mechanisms driving this nucleation or patch differentiation process are being studied: (1) the trapping of resources from the environment, (2) the modification of soil structure, and (3) facilitation between plant functional types. Concerning the first mechanism, the research focuses on the links and fluxes of water and sediments between gaps and vegetated patches. The second mechanism is addressed through the study of the differential changes of soil structure that occur in vegetated patches, compared to bare ground, and their hydrological implications. Research on the third mechanism deals with the positive interactions between shrubs and their herbaceous undergrowth that contribute to an increased performance of the vegetated patches.

3.1.1. Trapping of resources by vegetated patches

It has been suggested that spatial patterns of sparse vegetation in drylands adapt themselves in such a way as to maximise the harvest of water resources (Puigdefabregas and Sanchez, 1996). Two conditions should be met for this hypothesis to hold: (a) plant clumps must develop mechanisms to harvest water from bare patches, and (b) the proportions and dimensions of vegetated and bare phases of the mosaic must be coupled. Our field observations provide evidence for the existence of both conditions.

Plants can harvest water from contiguous bare areas by extending their root systems into them, or by catching the runoff generated by them. The first strategy has been demonstrated in sparse shrublands of *Retama sphaerocarpa* (Haase et al., 1996b) by putting labelled water at different depths, up to 28 m, in the soil of bare patches. After 24 h the tracer was identified in the *Retama* canopies.

The distribution of fine root biomass (Ø < 5 mm) in the soil profile helps also to assess how far the roots have extended into bare ground patches. This was determined along the studied catena in Rambla Honda. Soil samples were taken in cubes of 10 cm^3, at each 10 cm from the soil surface to the basal rock or down to a depth of 100 cm, in two columns per measurement area, one under a plant clump and the other in bare ground (Puigdefabregas et al., 1996).

Results show (Fig. 3) that in *Retama* stands the distribution of root biomass under bushes is not different from the distribution in intershrub clearings, confirming the uniform occupation of roots over the whole area. At the other extreme, in *Stipa* stands root biomass was found to be less at all depths in soils from bare ground areas than in soils from vegetated patches, which indicates that roots are concentrated below the tussocks, and do not exploit the areas between them. Soils in *Anthyllis* stands show an intermediate pattern. Upper roots extend beyond shrub canopies, while below 20 cm depth fine roots concentrate below the crowns of *Anthyllis*, probably attached to the vertical tap roots.

The significance of water harvesting from bare ground in clearings has been demonstrated in *Stipa tenacissima* stands (Puigdefabregas and Sanchez, 1996), by excluding tussocks from the overland flow generated by the bare patches. The results showed that both annual average soil moisture content and

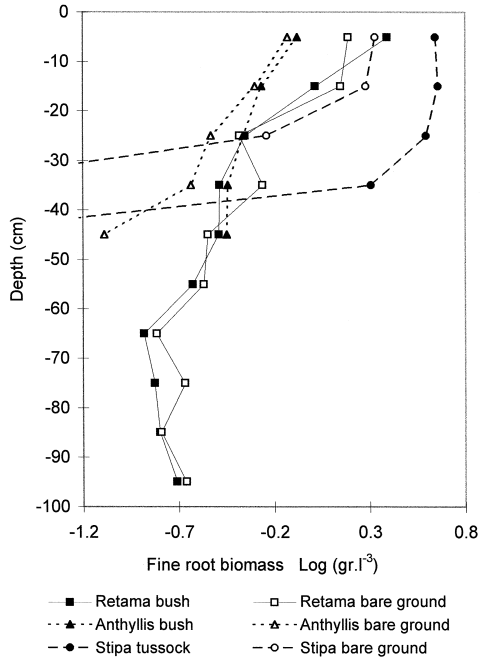

Fig. 3. Distribution of fine root biomass in the soil profile, under vegetated clumps and in nearby bare ground areas.

plant growth were significantly less in tussocks that were excluded from overland flow than in controls (Table 2). The role of tussocks as runoff sinks and infiltration sites has also been reported in other field studies using rainfall simulation experiments (Bergkamp, 1996; Bergkamp et al., 1998).

Measurements of runoff and sediment fluxes, made at a large number of sites with troughs of 0.5 m length in *Stipa tenacissima* stands, showed highly significant differences according to the position relative to the tussocks (Table 3). The flat areas or treads

Table 2
Effect of excluding overland flow from uphill bare-ground patches on leaf length and moisture content of the uppermost 5 cm soil layer, in a *Stipa tenacissima* stand, at Rambla Honda

	Leaf length increment ($cm\ stem^{-1}\ yr^{-1}$)	Soil moisture annual average (0 cm–5 cm) (vol%)
Control	23 ± 4	1.6 ± 0.09
Overland flow excluded	10 ± 3	1.3 ± 0.09

Mean values and 1 SE. Treatment values are significantly different from controls at $P < 0.001$ (t-test). Source: (Puigdefabregas and Sanchez, 1996).

Table 3
Mean relative values and 1 SE of runoff and sediments collected in different microsites of mound and swale complexes, in *Stipa tenacissima* stands, at Rambla Honda in 11 rainfall events

	Runoff	Sediment yield
Bare ground	1.21 ± 0.07	1.26 ± 0.10
Tread	0.54 ± 0.08 ***	0.66 ± 0.11 ***
Tussock (riser)	0.60 ± 0.11 ***	0.56 ± 0.14 ***
Lateral swale	1.67 ± 0.19 ***	1.65 ± 0.23 *

Two hillslopes were sampled, each with two rows of collector troughs, and 12 troughs in each row. Relative values are calculated from ratios of the amounts collected by each trough to the mean of 12 troughs of its row in its hillslope position. Significance of the differences against bare-ground patches: *** $P < 0.01$; ** $P < 0.05$; * $P < 0.1$. Source: (Puigdefabregas and Sanchez, 1996).

just uphill of the tussocks are the main sinks of overland flow and sediments coming from bare patches. They intercept about 50% of both water and sediments. Because of the recurrent deposition, these sites have become enriched with sand and have a smaller slope gradient than the rest of the hillslope. These, two features further reinforce infiltration and deposition (Puigdefabregas and Sanchez, 1996).

In cases where vegetated patches were shown to be hydrologically linked to the neighbouring uphill bare ground areas, it has been postulated that the average downhill lengths of bare patches and plant clumps, is such that the harvest of runoff by the latter is maximised. The optimum length of bare areas can be expected to depend on the rate at which the runoff coefficient decays with slope length, while the average length of vegetated patches can be expected to be controlled by their efficiency as runoff sinks. Predictions of the downhill length of both bare and vegetated patches, based on these assumptions, agreed reasonably well with the observed values in an old *Stipa tenacissima* stand at Rambla Honda (Puigdefabregas and Sanchez, 1996).

3.1.2. Modification of soil structure

Significant differences in the structure of the topsoil layers were found between plant clumps and clearings at Rambla Honda. They have been interpreted as an effect of the nucleation process in sparse vegetation on the soil hydraulic properties. In the following section, the observed patterns of topsoil differentiation in the two hillslope sectors, the sedimentary fill at the footslope and the rocky upperslope, are described in terms of soil profile morphology, rock fragment cover and particle size distribution.

3.1.2.1. The sedimentary fill. The whole soil mantle from both the fluvial terrace and the alluvial fan is covered by a stone pavement consisting of a usually less than 1 cm thick layer of fine gravels (5 to 20 mm in diameter). This gravel essentially consists of micaschists, and is bedded along the main plane (Fig. 4a). Under bushes, this rock fragment cover is mixed with, and often covered by, litter, which is far more abundant than in bare ground patches.

Below the stone pavement we can observe a 0.5 to 2.0 cm thick layer formed by very fine gravel and coarse sand (particles from 0.5 mm to 5 mm in diameter), also bedded along their main plane, showing an unclear inverse graded bedding (i.e., coarse particles at the top), and a low proportion of finer particles. In bare patches, this layer is more washed-out than in plant-covered patches, where sand particles and sand-size organo-mineral aggregates are mixed.

Under this washed-out horizon appears a massive, 2–10 mm thick layer, formed by closely packed very fine sands, only crossed by vertical or sub-vertical cracks and very fine roots. This horizon is considered to be a washed-in layer, with a crust-type morphology. When exposed at the soil surface, due to erosion of the overlying gravel and sand layers, it forms a real crust, in the wet season sometimes

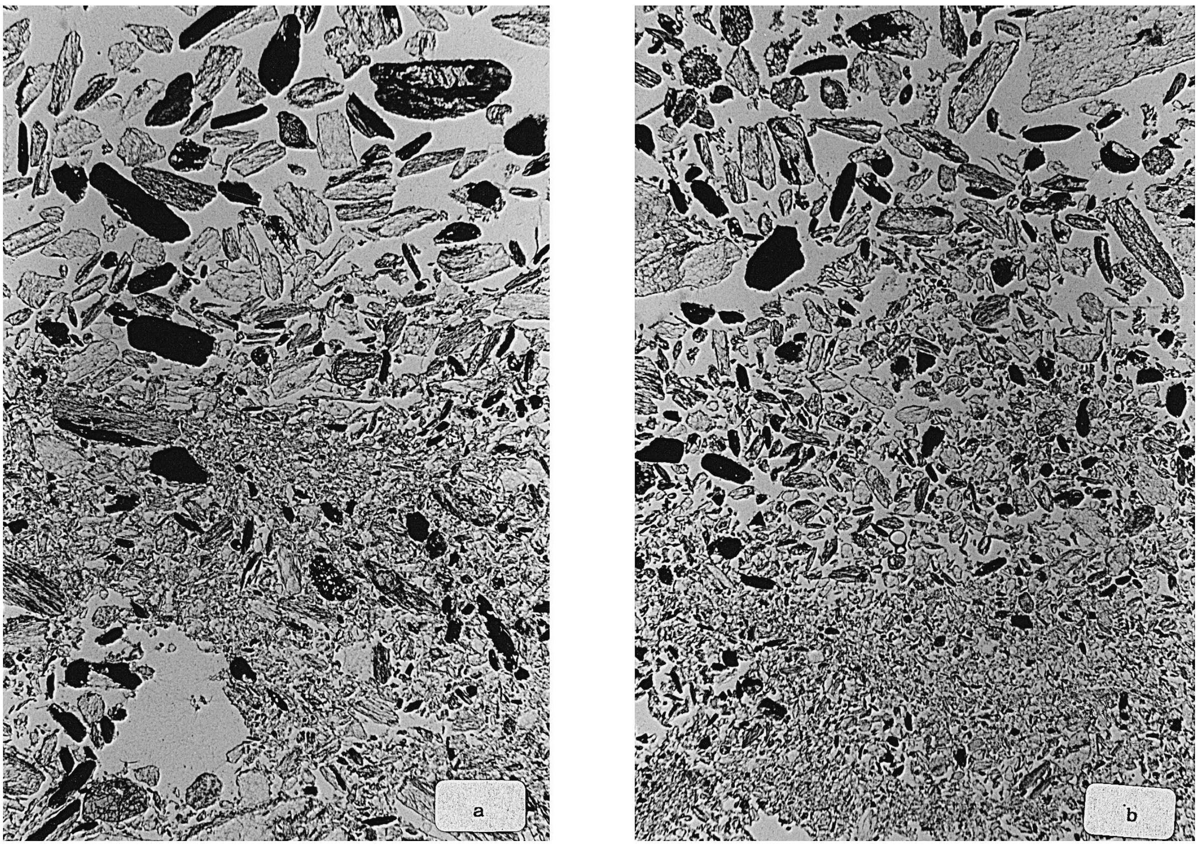

Fig. 4. Partial view of the soil surface horizon in thin section, in a bare ground patch (a) and under a *Retama sphaerocarpa* bush (b), both in the lower part of the alluvial fan, at the Rambla Honda field site. In (a) the washed-out layer (upper half of the frame) constituted by mineral particles (mostly micaschist and some quartz fragments) can be distinguished from the washed-in layer (middle of the frame). In (b) notice the downward trend of decreasing particle size, and the washed-out layer (upper 2/3 of the frame) constituted by mineral particles and some organo-mineral aggregates, above the washed-in layer (lower 1/3 of the frame). The real size is 6.7 mm × 10 mm.

covered by mosses. In plant-covered patches, this washed-in layer can be morphologically identified (Fig. 4b), but its textural difference from other layers is analytically less significant than in bare patches, either because of its smaller thickness, 1–5 mm, and the difficulties in obtaining samples, or because it is mixed with coarse sand and gravel.

To a certain extent, the whole structure of these surface layers is similar to what has been described as a *sieving crust* (Valentin and Bresson, 1992); however, the upper layer of the Rambla Honda *sieving crust* is constituted by a coarse pavement and the overall infiltrability is much higher than what stated by the former authors in soils from semi-arid West Africa.

Underneath this sieving crust appears a 10–15 cm thick, unsorted (i.e., texturally heterogeneous) horizon. It is formed by an unoriented mixture of gravels and fine earth (particles < 2 mm), with abundant macropores and very fine roots. Soil structure, is weakly developed, and it grades from a fine to medium crumb structure, in the lower part of the alluvial fan system, to a moderately developed, subangular medium to fine block structure, in the upper part of the alluvial fans. This structure, lacks bioturbation features and is particularly noticeable around and among fine roots. It is interpreted as the preserved remains of a former Ap horizon (i.e., anthropically perturbed). The main morphological difference between the soils of bare and vegetated patches concerns the abundance of organo-mineral aggregates, which is greater in the latter than in the former.

Below 15–20 cm depth, a series of more or less bedded layers consisting of either a mixture of gravel and sands or pure sands (depending on their colluvial or alluvial origin), form a number of C horizons (IC, IIC, IIIC, . . .) down to the micaschist bedrock which is found at 8–18 m depth. Neither morphological nor analytical differences were found between bare and vegetated patches at these depths. The lack of pedoturbation explains why sedimentary structures are so well preserved.

3.1.2.2. The upper hillslope. The soil mantle in the rocky upperslope is sparsely covered by *Stipa tenacissima* tussocks, which have created a distinct micro-relief (Puigdefabregas and Sanchez, 1996), including depositional treads or terracettes upslope from the tussocks, risers at the downslope front of terracettes, and bare ground patches.

(a) In bare patches, the soil surface is covered by a discontinuous structural crust between large, mostly embedded, rock fragments (Fig. 5a). The crust itself is less than 1 mm thick but the surface horizon under the crust, is several centimetres thick and is quite massive, with few and very narrow macropores.

(b) In the depositional treads, soil surface differentiation is similar to the sieving crust found in the footslope sedimentary fill. An uppermost layer, in general less than 10 mm thick, of washed-out fine gravel, and a compact, gravelly loamy, layer of washed-in particles which is about 5 mm thick (Fig. 5b). In some cases, this washed-in layer can be non-existent or undetectable. Underneath these two layers, there is a soil mass of alternating, but less delineated, layers of coarse and fine particles, mixed with organic components and aggregates, in a moderate to strong structure, with abundant vesicles and other macropores. Evidence of bioturbation is present but scarce.

(c) In the risers, where the tussocks actually grow, the soil surface is covered by a litter layer of decaying leaves and stems. The upper soil layer is only a few millimetres thick and mostly formed by coarse-sand-size organic fragments and organo-mineral aggregates. Underneath, there is an undifferentiated soil mass, which is loamy with unoriented gravels, similar to the one observed in the treads but with more evidence of bioturbation and greater macroporosity.

The soil structural patterns described above suggest that a differentiation of a surface washed-out layers, which is enriched in gravels, and a sub-surface washed-in layers, enriched in fine sand and silt, occurs across the hillslope. This kind of textural differentiation has been also reported in dryland environments of the Sahel (Valentin and Bresson, 1992; Bresson and Valentin, 1994).

The washed-in/washed-out ratio (FPR) of fine particles (fine sand + silt + clay), provides a useful index to monitor the intensity of this process. The textural differentiation may be driven by splash, percolation and downhill runoff. After the cessation of agriculture, the top soil layer which was initially mixed by ploughing (i.e., FPR = 1), became progres-

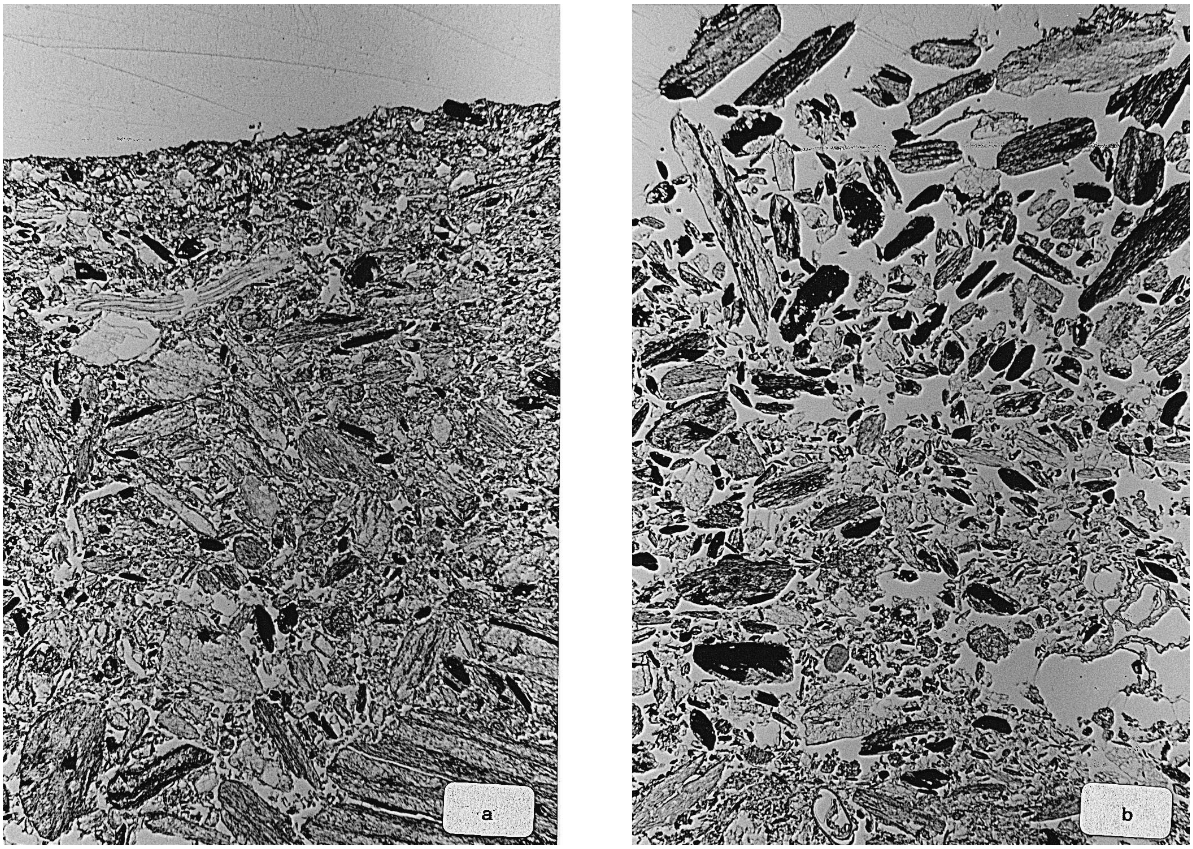

Fig. 5. Upper centimetre of a soil profile in thin section from a bare ground patch (a) and a depositional tread (b), just uphill from a *Stipa tenacissima* tussock, in the upper hillslope, at the Rambla Honda field site. In (a) below a sealed surface crust, the soil material (mineral, organic and organo-mineral particles) is quite compacted. In (b) a well delineated washed-out layer (upper half of the frame) overlays a less conspicuous washed-in layer (lower part of the frame). The real size is 6.7 mm × 10 mm.

sively differentiated in the course of time (i.e., FPR increases above 1) as shown in Fig. 6. FPR increases upslope along the alluvial fan, from the youngest towards the oldest abandoned fields. The smallest FPR values are found at the upper hillslope sector which was never cultivated, probably by the effect of the tussock migration across the space.

Beneath bushes and tussocks, the differentiation process is slower or even disturbed by the action of roots and soil biota that feed on the litter below the canopies. Under canopies, fine sediments either transported by overland flow or from dry atmospheric deposition (Domingo et al., 1994) are trapped by bushes and tussocks, and counteract the differentiation trend by stimulating the formation of organo-mineral aggregates.

3.1.3. Implications of the modification of top soil layer structure for soil hydrology and soil biological activity

The weaker development of washed-in layers and the greater inputs of litter in the soil beneath plant clumps are associated with higher organic matter contents, a larger pore volume and water storage capacity, and a greater saturated hydraulic conductivity (Table 4). Spatial variation in these properties is expected to give rise to differences in hydrological behaviour between soils beneath bushes and soils of bare ground patches.

Infiltration rates in vegetated patches are generally thought to be greater than in bare ground patches (Lyford and Qashu, 1969; Scogging and Thornes, 1980; Bergkamp, 1996). In general, the results from

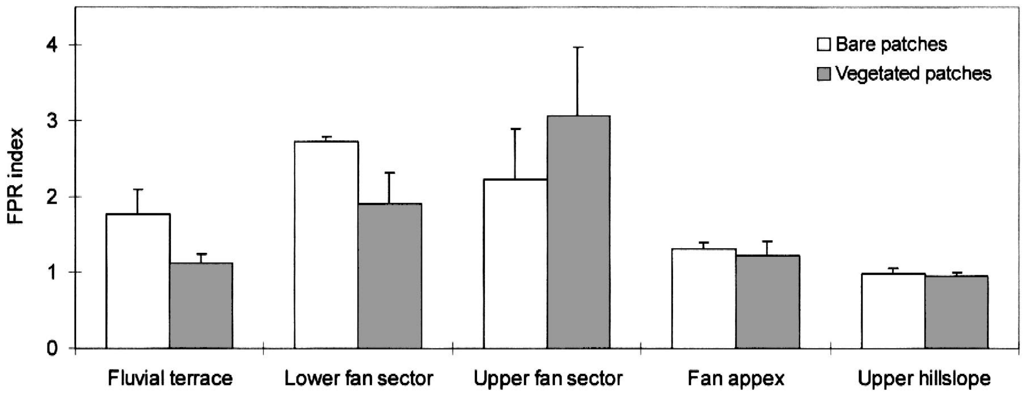

Fig. 6. Differentiation index (FPR) from surface horizons below vegetated and bare ground patches at the Rambla Honda field site. (FPR = ratio of ''fine sand + silt + clay'' between washed-in and washed-out layers; error bars = 1 SE).

Rambla Honda confirm this assumption. Saturated soil conditions occur more frequently and last longer in bare patches, so that these areas become the main sources of runoff. Top soil layer morphology provides clues for such behaviour. In the fan (Fig. 4a), the subsurface washed-in layer is more compacted in the bare areas than under bushes, and hence may play the role of a sealed layer. In the upper hillslope (Fig. 5a), bare areas are covered by both embedded rock fragments and structural crusts which also enhance overland flow (Poesen and Lavee, 1994).

However, the soils under plant clumps show a very varied wetting behaviour, and in some cases, they are responsible for ephemeral and spatially discontinuous overland flow. The analysis of wetting phases in a *Stipa tenacissima* stand (Puigdefabregas and Sanchez, 1996) shows that the soils in vegetated patches may wet very quickly to saturation, and become ephemeral runoff sources during the first stages of the rainfall event. However, runoff coefficients from rainfall simulation tests (50 mm h^{-1} during 30 min) carried out along the catena, do not show significant differences between vegetated and bare patches (Nicolau et al., 1996). In some cases, particularly in the *Retama* stands of the lower fan sector, the runoff coefficient of soil below bushes may be twice the value recorded on soils in gaps (Fig. 7). Hydrophobicity of the organic litter has been claimed as a cause of this behaviour (De Bano, 1981), as shown by the early peak and further decrease of overland flow in rainfall simulations on soils under *Retama* bushes (Fig. 8).

Drying phases have been studied in a *Stipa* stand (Puigdefabregas and Sanchez, 1996). During the cold season, at low transpiration rates, water is lost faster from bare-ground than from vegetated patches, and in both cases near-surface layers loose water faster than deeper ones. In contrast, during the warm season, when transpiration rates are higher, soil moisture content in the near-surface layers of both bare

Table 4
Organic matter, water content at 0.033 MPa (field capacity) of the fine earth fraction, and saturated hydraulic conductivity (K_{sat}) ($\pm$1 SE) of the surface soil horizons, in the three representative sectors of the Rambla Honda catena, under vegetated and bare-ground patches

	Organic matter (%)		Water content (g cm^{-3})		K_{sat} (m day^{-1})	
	Bare-ground	Plant clumps	Bare ground	Plant clumps	Bare ground	Plant clumps
LFS	1.4 $\pm$ 0.1	4.8 $\pm$ 0.1	0.24 $\pm$ 0.001	0.32 $\pm$ 0.013	1.13 $\pm$ 0.31	1.64 $\pm$ 0.53
UFS	2.1 $\pm$ 0.4	4.8 $\pm$ 0.1	0.21 $\pm$ 0.001	0.36 $\pm$ 0.005	0.25 $\pm$ 0.08	0.37 $\pm$ 0.07
UHS	4.6 $\pm$ 0.7	6.6 $\pm$ 0.2	0.32 $\pm$ 0.001	0.40 $\pm$ 0.063	0.48 $\pm$ 0.16	1.42 $\pm$ 0.52

LFS = lower fan sector; UFS = upper fan sector; UHS = upper hillslope sector.

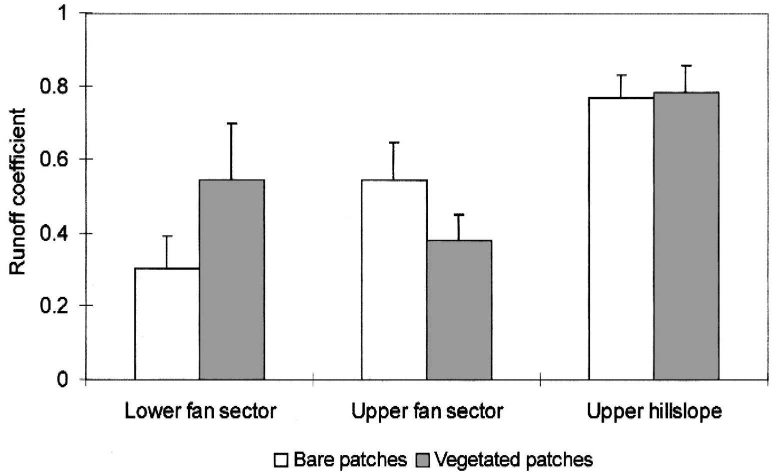

Fig. 7. Runoff coefficients from rainfall simulation tests in plant covered surfaces and bare ground along the Rambla Honda catena. Error bars = 1 SE. Source: (Nicolau et al., 1996).

ground and vegetated patches decays at similar rates, both of which being greater than those of the deeper soil layers. Seasonal averages of volumetric soil moisture contents over the three canopy types along the catena, are in general slightly lower under vegetated than in bare patches (Fig. 9). However, the differences are scarcely significant, probably due to the mulching effect of canopies, litter and annual plants. This mulching reduces direct evaporation from the soil beneath plant clumps (Domingo et al., 1999),

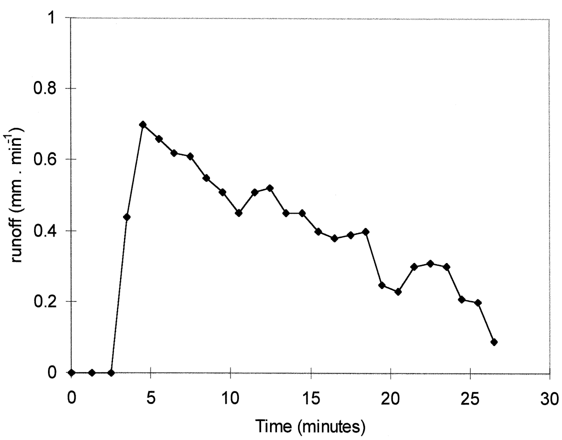

Fig. 8. Overland flow hydrograph from a rainfall simulation experiment (50 mm h^{-1}) on the soil below a Retama bush. Runoff reduction with time may be due to initial hydrophobicity of the dry litter. Source: Nicolau et al., 1996.

and tends to compensate for their greater transpiration, compared to bare ground.

In spite of the lack of significant differences in water content, soil chemical, physical and structural properties allow for a greater biological activity in vegetated patches than in the open. As a consequence, litter decomposition rates are higher under plant clumps than in bare patches. At Rambla Honda, this has been studied using cellulose decomposition tests, such as the cotton strip assay (Sagar, 1988). Cotton strips were buried at 5 cm below the soil surface, beneath plant clumps and in bare patches (Puigdefabregas et al., 1996). As expected from their higher soil organic matter content, cellulose decomposition rates are greater beneath plant canopies than in the open (Table 5), the effect being particularly strong in late spring, when soil temperatures and moisture are not limiting.

3.1.4. Bush-herb facilitation

Annual grasslands are widespread in the semi-arid Mediterranean landscapes. In Rambla Honda, their spatial distribution is patchy, as they concentrate beneath bushes or around tussocks of *Stipa tenacissima*. This feature suggests some kind of mutual facilitation between shrubs and herbs. In order to confirm this hypothesis, a *Retama sphaerocarpa* stand, located in the channel bed of Rambla Honda, was studied (Pugnaire et al., 1996a). A set of physio-

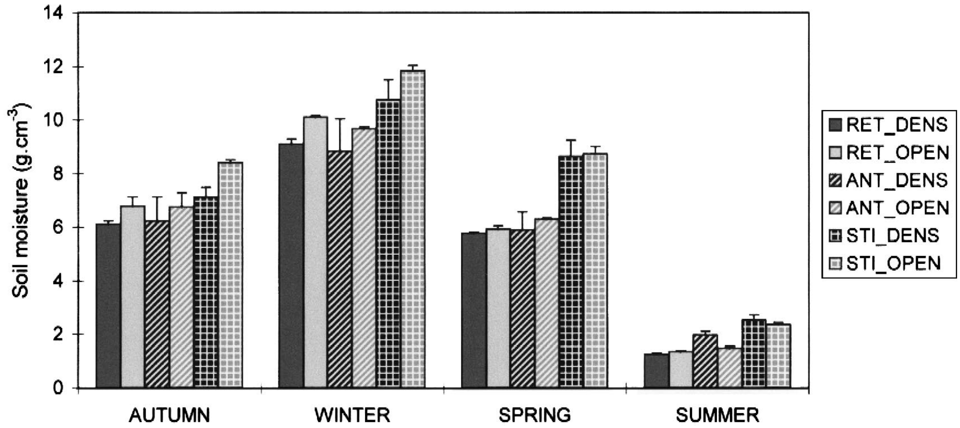

Fig. 9. Seasonal averages (1992–1997) of soil moisture content (g cm^{-3}) below canopies and in bare ground, in the three vegetation types of the Rambla Honda catena. AU = Autumn; WI = Winter; SP = Spring; SU = Summer; RET = *Retama*; ANT = *Anthyllis*; STI = *Stipa*; DENS = under canopies; OP = bare ground. Data were obtained gravimetrically after the procedure described in (Puigdefabregas et al., 1996), and transformed to volumetric values using soil density measures. Error bars = 1 SE.

logical and morphological attributes was recorded in two ''coupled'' species, *R. sphaerocarpa* and the biannual herb *Marrubium vulgare*, using individuals that were either growing together or isolated.

Performance was assessed in terms of leaf or cladode mass, specific leaf area (surface/weight ratio), nitrogen content per branch, and shoot water potential at midday. It was found (Fig. 10) that both species perform better when growing together than when growing isolated.

These results provided evidence of reciprocal facilitation between bushes and their herbaceous undergrowth in the fertility islands of sparse vegetation, but could did not be used to show how each partner benefited from living together. Further experiments were performed to obtain this type of information (Moro et al., 1997a; Moro et al., 1997b).

Three sets of soil samples from the same *Retama* stand, were collected along transects from the centre to the edge of a number of bushes. They were kept at field capacity in pots, in the lab. One series of pots was left until the seeds which were naturally in the samples emerged and matured. A second series of pots was treated with several amounts of *Retama* litter. A third group of samples was used for a bioassay and was sown with barley. A second experiment consisted of performing the same treatments on samples collected from only one position, namely from the centre of the plant clump. This time, the samples were placed in pots, and left in the field,

Table 5
Cellulolithic activity (±1 SE) at the uppermost mineral soil horizon, on bare-ground and vegetated patches, in the different vegetation types of the Rambla Honda catena

Upper mineral soil layer		C/N mean	*a* CRR (yr^{-1}) $n=5$ Under bush	*b* CRR (yr^{-1}) $n=5$ Gap	$(a-b)/b$
Early Spring 18 Mar.–15 Apr. 1992	*Retama*	5,25	18,45 ± 1.14	12,94 ± 2.08	0,43
	Anthyllis	4,79	13,12 ± 1.03	10,9 ± 0.93	0,20
	Stipa	8,7	14,09 ± 2.55	8,89 ± 2.39	0,58
Late Spring 22 Jun.–24 Jul. 1992	*Retama*	5,25	31,41 ± 4.41	15,91 ± 2.08	0,97
	Anthyllis	4,79	23,14 ± 4.30	11,2 ± 1.39	1,07
	Stipa	8,7	15,85 ± 3.6	8,7 ± 1.13	0,82

Values are expressed as cotton rotting rates (CRR yr^{-1}). CRR = $CTS50^{-1}$, with CTS50 = time (years) to 50% of cotton strip tensile strength loss (Sagar, 1988). Source: (Puigdefabregas et al., 1996).

along transects from the centre to the edge of the bushes.

Results showed that (a) chemical soil fertility decreases from the centre of the plant clump to the bare areas outside, and (b) the addition of litter decreased species richness, the number of emerged seedlings and biomass production. The combination of decreasing trends of soil fertility and litter accumulation from the centre to the edge of the bush, together with the microclimatic patterns of temperature and irradiance, causes a maximum of biomass production at intermediate positions along the transect (Fig. 11). The high proportion of litter from annual species in these intermediate positions increases the mineralisation rate and hence the availability of nutrients to the shrub. The association between bush and undergrowth results in a greater availability of resources in the ''fertility island'' from which both partners benefit.

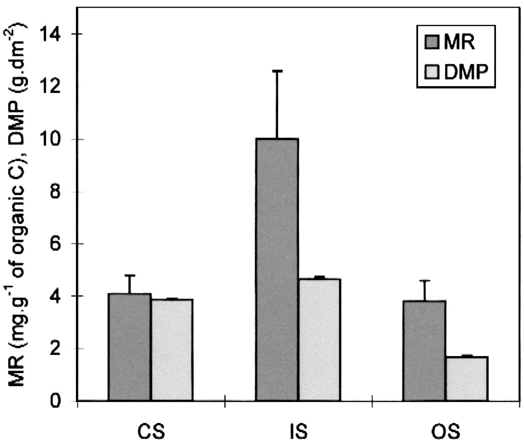

Fig. 11. Two characteristics of soils from the centre (CS), intermediate (IS) and edge (OS) positions under the canopy of *Retama sphaerocarpa* shrubs. MR = mineralisation rate (g kg^{-1} of organic C) (Moro et al., 1997b); DMP = dry mass production of barley plants grown in soils from the three positions in the understorey (Moro et al., 1997a). Error bars = 1 SE.

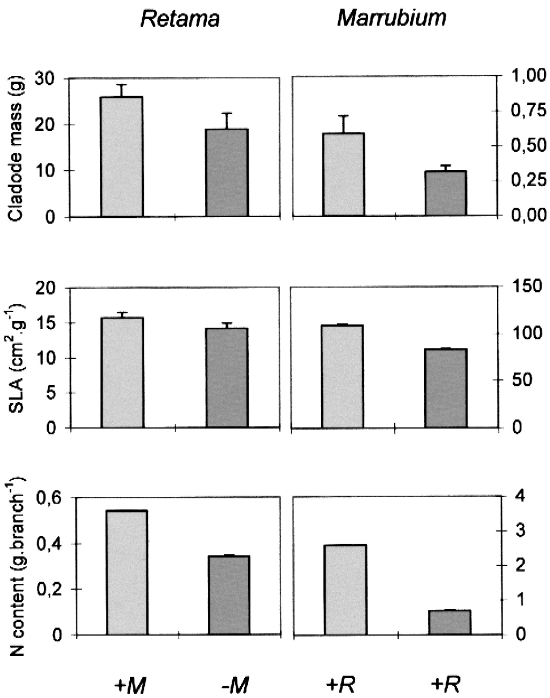

Fig. 10. Dry mass of cladodes or leaves per branch, specific leaf area (SLA), and nitrogen content in *Retama sphaerocarpa* (*R*) and *Marrubium vulgare* (*M*) growing in association (+ *R*, + *M*) or alone (− *R*, − *M*) at Rambla Honda. Nitrogen content is expressed as mass per 3-yr-old branch in *Retama* and per plant in *Marrubium*. Data represent means; error bars represent 1 SE; those with different letters are significantly different at $P > 0.05$ (*t* test). Source: (Pugnaire et al., 1996a).

These functional linkages through mutual facilitation between plants lifeforms growing in the same patch, reinforce the environmental differences between fertility islands and their surroundings, and hence promote spatial heterogeneity at the patch scale. Moreover, the interaction between both partners creates dynamic circular zones of enhanced activity in the soil just beyond the edge of the plant clump that presumably migrate outwards as the whole patch grows.

3.1.5. The nucleation process in time and space

If the formation of resource islands were a merely additive process, resulting from the increasing area covered by the plants in the clump, one might expect some regularities in the associated patterns of soil properties. Extensive properties of the soil, that is those that are expressed in absolute terms, such as the accumulated mass of the mound, total nutrient content or total water storage capacity, would show a linear increase at a rate similar to that of the canopy. Intensive properties of the soil, being those that are expressed in relative terms, such as concentrations of nutrients, soil organic matter, soil bulk density, etc., would not change with the growth of the canopy.

On the other hand, if positive feedback mechanisms were involved in the formation of resource islands, one might expect that extensive soil properties would change at greater rates than the expansion of the canopy, possibly following non-linear trends, and that intensive properties would not remain constant.

Field evidence supporting the positive feedback hypothesis was obtained in Rambla Honda, by studying the changes along an age gradient of *R. sphaerocarpa* bushes (Pugnaire et al., 1996b).

The extensive properties of soils beneath bushes (Fig. 12) show non-linear changes, their relative increase rate being larger in the older than in the younger stages. This acceleration of change with time is more pronounced for nutrients, like nitrogen and phosphorous, than for total water storage capacity or mound mass.

The intensive properties do not remain constant. For example, relative increase rates between 5–9% yr^{-1} were recorded for soil organic matter and

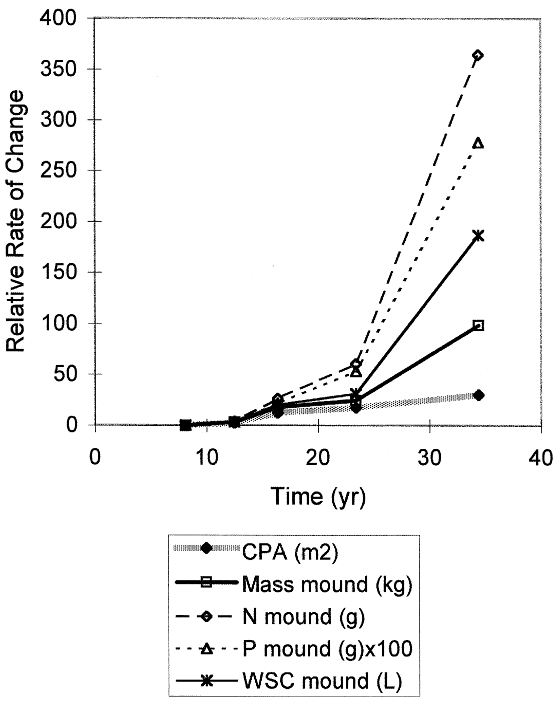

Fig. 12. Relative rates of change of some soil properties in mounds under *Retama* bushes of different ages. CPA = Canopy projected area; WSC = water storage capacity; N = Nitrogen; P = Phosphorous. Source: (Pugnaire et al., 1996b).

nutrient concentrations, as well as for the clay + silt content and electrical conductivity. Relative decrease rates of −0.3 to −1.3% yr^{-1} were observed for soil bulk density and for the red/far red radiation ratio below the canopy. Species richness and annual plant biomass also increase with time. Qualitative changes in the understorey, like the appearance of perennials and the displacement of drought resistant species by more mesic ones, occur in the later stages of the age gradient.

Some processes that presumably operate in a non-linear way over time, may be claimed to underlie the changes described above, and to contribute to the creation of spatial heterogeneity and resource islands in arid environments. Canopies intercept and funnel down dust and atmospheric aerosols. In this way plants contribute to the accumulation of clay + silt, nutrients and salts in mounds around their stems. This effect has been reported in the area, particularly concerning the inputs of Na^+, K^+, Ca^{2+} and Mg^{2+} (Domingo et al., 1994). Nitrogen fixation and the increased mineralization rate of the soil organic matter may also reinforce the enrichment of nutrients beneath shrub canopies. As a result, the availability of resources increases, while physical soil conditions and the microclimate below the canopies become more favourable for plant growth.

Once resource islands have been built up, they persist for a time after the shrubs which contributed to their formation have died. During this time, resource islands decay and the soil properties will become similar to those of the surrounding bare ground areas. On the other hand, the resource islands themselves are not fixed in space but are mobile to some extent, as they die out and occupy new space either through seed dispersal or vegetative growth.

It may be anticipated that this mobility governs the cell replacement rates in the two phase vegetated-bare ground mosaics. Therefore, patch mobility is a key issue into understanding and modelling changes of land condition. As a consequence of the positive feedback mechanisms described above, the persistence of resource islands for a long time in the same place, would lead to a very pronounced differentiation of the soil and understorey from adjacent inter-shrub clearings, with strong implications for land degradation risks. On the contrary, fast rates of replacement between vegetated and bare patches in the resource island system tends to blur the spatial heterogeneity of the soil and the overall risk of land degradation diminishes.

Data from Rambla Honda on soil properties from plant clumps and clearings, indirectly support this hypothesis. The most pronounced contrasts between plant clumps and clearings, in terms of organic matter content and texture of the topsoil, are found in *Retama* stands, the least important differences have been recorded in the upper hillslope covered with *Stipa*, while *Anthyllis* stands show intermediate values (Table 4, Fig. 6).

Retama stands occupy the areas that were abandoned most recently from agriculture, and the replacement process between patches has still not occurred. The area occupied by *Anthyllis* was the first to be abandoned, these shrubs are short lived and several recruitment episodes have been detected from size distribution and spatial analysis (Haase et al., 1996a; Haase et al., 1997). Therefore replacement rates between plant clumps and gaps are expected to be faster than for *Retama*. The *Stipa* stands have never been cultivated, and tussocks are known to change their shape and to migrate slowly (Sánchez and Puigdefábregas, 1994). Here, plant clump replacement has hence been operating for a sufficiently long period to blur spatial heterogeneity in many soil properties.

3.2. Interaction between spatial patterns and hillslope fluxes of sediments

Plant canopies not only work as passive semi-permeable ‘‘umbrellas’’ that intercept rainfall, overland flow or atmospheric deposition. They are living structures that interact with hillslope fluxes through changes of their shapes and their spatial organisation. The former are relevant at the patch scale, while the latter work at the stand scale.

The plant clump-gap mosaics that arise from nucleation processes in the vegetation of arid climates, have a spatial structure that interacts dynamically with the fluxes of water or sediments running along preferential directions. This phenomenon has implications for the water and sediment storage in hillslopes. Examples concerning sediment movements have been described for alpine (Gallart et al., 1993) and arid climates (Puigdefabregas and Sanchez, 1996), while the banded patterns known as tiger bush in the Sahel (Thiéry et al., 1995) are an example of mosaics developing in response to the redistribution of runoff. In Rambla Honda, some field research has been carried out to gain a better understanding of these readjustments between water and sediment fluxes and vegetation structures. Most of the work has been done on the interaction of *Stipa tenacissima* tussocks with the downslope movement of sediments. Results provide insight in the functioning of individual patch-gap systems (Sánchez and Puigdefábregas, 1994; Sanchez, 1995; Puigdefabregas and Sanchez, 1996)., and in the factors determining the spatial arrangement of whole mosaics across hillslopes (Puigdefabregas and Sanchez, 1996).

3.2.1. Interactions between fluxes and structures at the patch level

In flat areas, tussocks are circular in shape, and are constituted of modules or bundles of stems connected together. The inner part of the tussock is occupied by dead debris and old stems, while young stems are concentrated along the outer edge. The life cycle of the tussocks includes a building phase until the mature circular structure has been reached, followed by a senescence phase in which the modules become unconnected and the tussock breaks apart. Eventually, senescent tussocks may give rise to new tussocks from their isolated modules.

The tussock grows by layering, that is, young stems root when they bend over and touch the soil. This is a key process, which can be hindered by the mat of dead leaves or by the pressure of the sediments that accumulate uphill of the tussock. Dead leaves cause the radial growth to become delayed and accumulated sediment cause the shape of the tussock to become modified, which in turn changes the amount and spatial distribution of subsequent sediment depositions.

These field observations were formalised in a cellular automata model that describes the changes of tussock shape, the age structure of stems and the associated micro-relief (Sánchez and Puigdefábregas, 1994). The model includes a geomorphological routine that describes the sediment transfer between grid cells, and a biological routine that simulates the space occupation and the tussock life cycle.

The geomorphological routine circulates the sediments using a development of the Musgrave equation (Kirkby and Neale, 1986) which incorporates splash and wash parameters

$$S = k_1 g + k_2 Q^2 g^2$$

where S stands for sediment discharge, g is the slope gradient, Q stands for overland flow, while k_1 and k_2 are splash and wash parameters that in turn, are influenced by vegetation.

The biological routine simulates the occupation of new cells from vegetated neighbours. It involves a probabilistic function that includes a maximum growth rate which is restricted by three terms, an age dependent decrease of branching rate, a vegetative influence of leaves and litter which is exerted by each vegetated cell up to a maximum distance around, and a sediment influence from upslope.

The results of the simulation experiments performed with this model (Fig. 13) show an acceptable degree of realism (Sánchez and Puigdefábregas, 1994). At low growth rates, the influence of litter determines the circular shape of the tussocks and the radial structure of stem ages. At high growth rates, the stems are able to escape from the litter influence, and the tussocks show less compact and more irregular shapes. By increasing the sediment flux, circular tussocks become elongated, with their longer axis

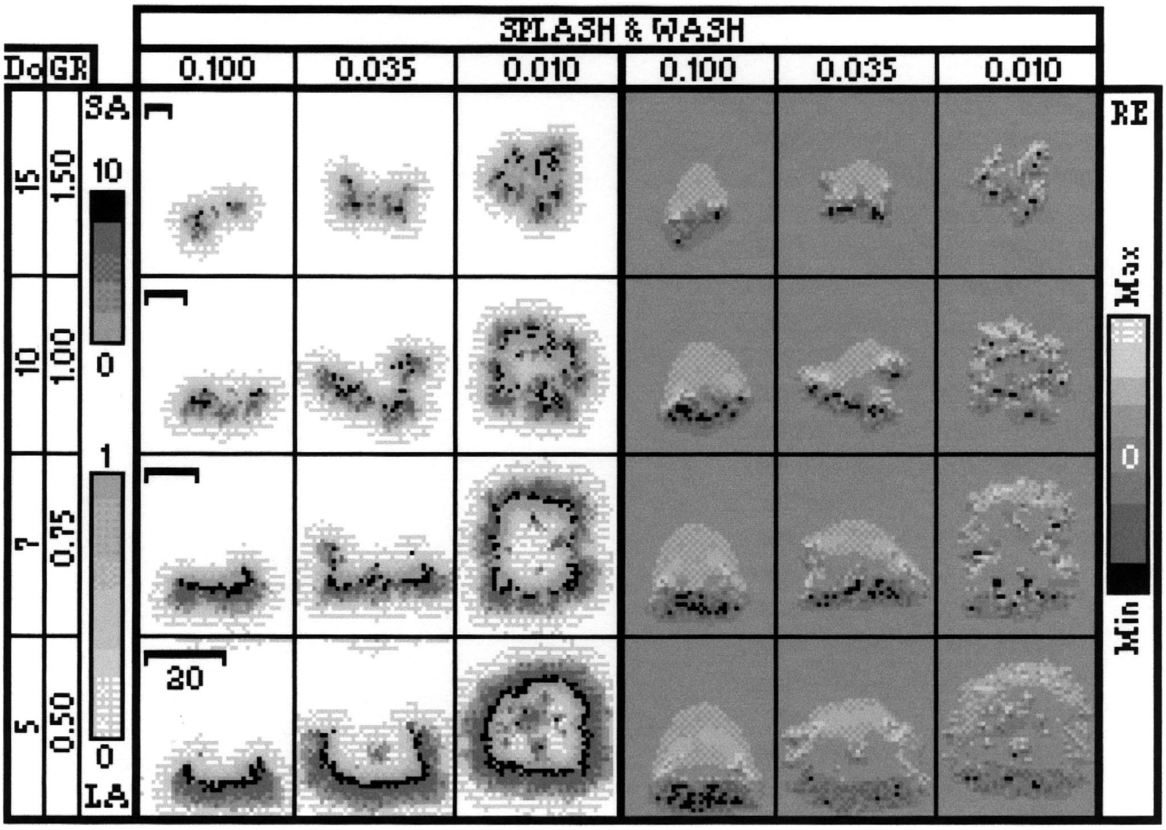

Fig. 13. Simulations of tussock (left-hand image) and micro relief (right-hand image) developments in sloping areas, using a cellular automata model. The figure shows the outputs of the model using three values of sediment circulation defined by splash and wash parameters that increase to the left, and four values of stem growth rate (GR) that increase upwards, and their associated maximum distance of leaf vegetative influence (D_0) on stem bending. The cells in the left column include a scale bar showing the equivalent of 20 length units in each row. In the left-hand image, dark shadings (up) display stem age at each cell and light shadings (bottom) indicate litter accumulation values. In the right-hand image, grey shadings display relief variations (RE) relative to the original background situation, and light and dark tones indicate increases and decreases of elevation, respectively. Source: (Puigdefabregas and Sanchez, 1996).

perpendicular to the slope direction, and treads of sediments accumulating uphill of each tussock.

3.2.2. Interactions at the stand level

Once the interactions between sediment fluxes and the spatial structure of tussocks was demonstrated, the next step consisted of answering the question whether the spatial arrangement of tussock populations in stands, also interacts with hillslope fluxes. If this were true, topographic variables that describe the potential intensity of water or sediment fluxes should show some association with the spatial patterns of tussocks.

In order to investigate this, an area of 4 ha (Fig. 14) was divided in quadrats with 10 m sides. For each quadrat semi-variograms were calculated from grey tones of pixels with 0.33 m sides, using aerial photographs (Puigdefabregas and Sanchez, 1996). The intensity of pattern in two directions, parallel and perpendicular to the slope direction, was quantified as the ratio of the first peak to the first trough of the semivariogram. This ratio is taken as an estimate of the degree of contrast between tussocks and bare ground bands along the direction of interest. Pattern intensity values were plotted against topographic variables for each quadrat. Specific catchment area and length slope factor (Moore and Burch, 1986) were selected as surrogates for runoff input and sediment transport capacity, respectively.

A trend was found between pattern intensity and the sediment transport surrogate (length slope factor) but not with the runoff surrogate (specific catchment area). The lack of association between pattern intensity and runoff confirms that the latter is relevant to

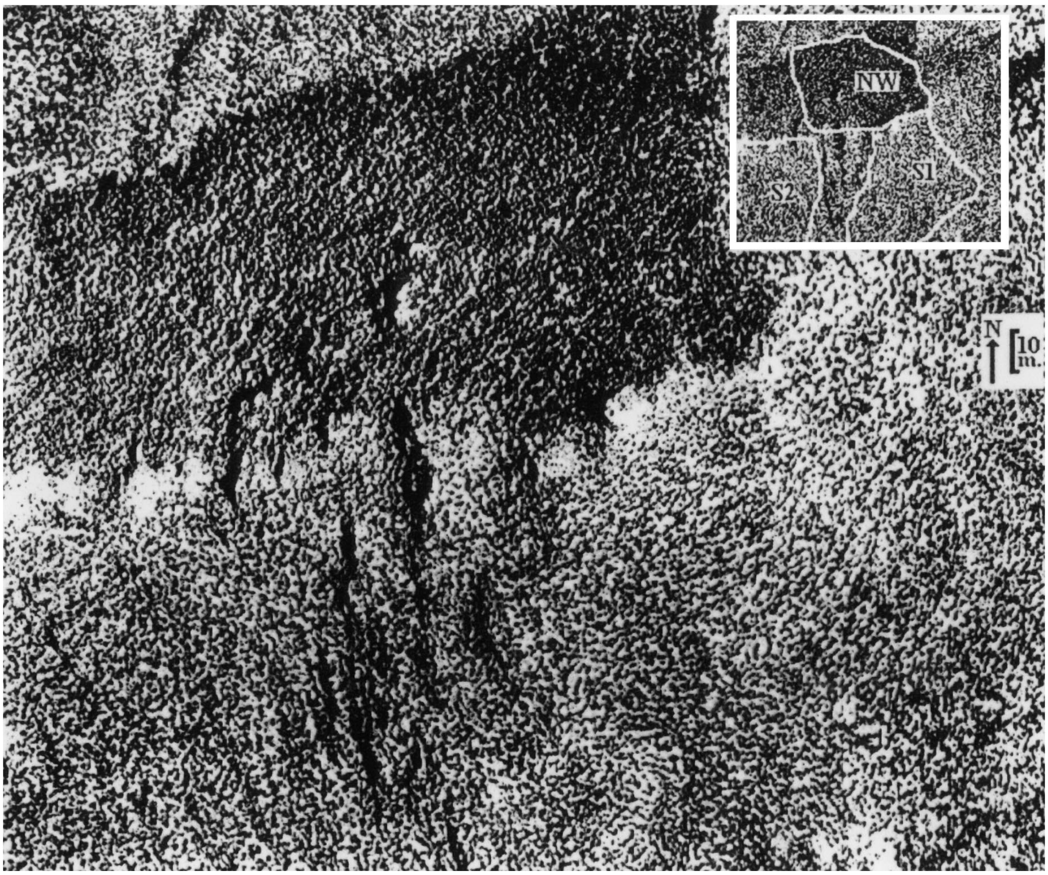

Fig. 14. Aerial photograph of a *Stipa tenacissima* covered summit at the Rambla Honda field site. The box in the upper right corner shows the sectors in which pattern and topographic analysis were conducted. Source: (Puigdefabregas and Sanchez, 1996).

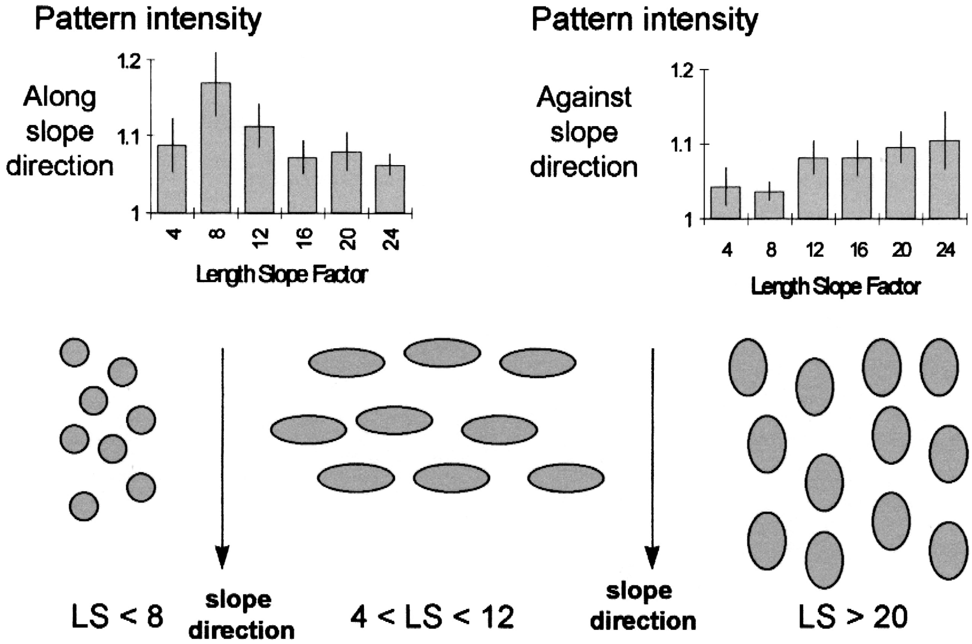

Fig. 15. Distribution of mean pattern intensity values among classes of the Length Slope Factor (LSF) as a surrogate for the transport capacity at the target quadrat in *Stipa tenacissima* stands at the Rambla Honda field site. The bottom part of the image shows the spatial patterns of tussocks associated with each range of LSF values. Pattern intensity is calculated as a ratio of the first peak to the first trough of the semi-variograms measured in the downhill and contour line directions. Error bars indicate 1 SE. Source: (Puigdefabregas and Pugnaire, 1999).

the plant clump/gap system, but not at larger scales, due to the short runoff lengths involved. The relation with sediment transport capacity (Fig. 15) may be interpreted as follows. If the sediment movement rate remains within certain limits (length slope factor values between 4 and 12) parallel stripes of tussocks develop along contours, as a spatial arrangement that maximises water availability to plants and soil storage at the hillslope level. At sediment fluxes below this tuning threshold, as happens in areas with small slope angles, the tussock-gap assemblages distribute at random. At sediment fluxes above the tuning threshold, plant clumps break off and rills form that hinder the establishment of plants in directions perpendicular to the slope. The result is a banded pattern, with stripes in the slope direction.

Patterns with stripes in directions perpendicular to the slope increase the resistances to downhill fluxes and favour the local storage of sediments and water in hillslopes (Gallart et al., 1993). In contrast, patterns with stripes parallel to the slope enhance runoff concentration, transport efficiency and rill initiation by increasing the catchment area and slope length in some sectors (Rogers, 1989). These conditions lead to diminished water availability and sediment storage in hillslopes.

4. Redistribution of water and sediments across hillslopes

In humid temperate climates, rainfall exceeds evapotranspiration, and relatively dense vegetation covers often ensure a high infiltration capacity of the soils. In such conditions, extensive saturated layers help to convey water downhill and to maintain hillslopes hydrologically connected most of the time (Whipkey and Kirkby, 1979). As saturated flow is driven by gravity, the spatial distribution of water is constrained by topography, so that saturated zones are likely to be found at the hillslope bases and in swales where subsurface flow converges (Kirkby and Chorley, 1967; Moore and Burch, 1986).

In arid climates evapotranspiration equals or exceeds rainfall for large parts of the year, rainfall events are few and short-lived, while vegetation is sparse, causing the infiltration capacity of the soils to be generally low. Saturated soil layers, if any, are discontinuous in space and time, and the hydrological connectivity of hillslopes is very poor. Spatial patterns of soil water content are less predictable, and soil moisture does not always increase downslope, as moist pockets may remain isolated in upslope sectors.

Hillslopes in arid climates often consist of an upper sector with shallow soils and frequent rock outcrops, and extensive alluvial fans at the lower part. In most cases, as in Rambla Honda, these sedimentary fills have been inherited from the past, they have been formed under different climatic and geomorphic conditions, and are currently being dissected by the channel network. It has been claimed that rocky upperslopes function as runoff sources while the main runoff sinks in the hillslope system are found in the contact zone with the sediment deposits of the footslope (Yair and Klein, 1973).

Hence, water and sediment redistribution on arid hillslopes is largely controlled by those properties that determine the efficiency of the rocky sectors and sediment fills as sources or sinks. Properties which are particularly significant are those that determine runoff lengths in interfluves, slope-channel connections, and the spatial ranges at which first order channels convey water and sediments.

Part of the research carried out at Rambla Honda is concerned with these aspects. Relevant information has been obtained from (1) the set of runoff plots and H flumes installed on the hillslope, (2) the manual and SBIBs-sensed soil moisture sampling program, and (3) the four sets of trough collectors installed on two north and a south-facing hillslopes, both characterised by a thin layer of colluvium and *Stipa tenacissima* vegetation (Sanchez, 1995). All this equipment and the sampling protocols are described and referenced in Section 2.

4.1. Runoff and sediment sources

Annual totals of specific runoff and sediment yield were obtained from measures carried out during one year in the set of runoff plots and hillslope sections (Table 6) (Puigdefabregas et al., 1996). These results shows that the rocky hillslope sectors and the upper parts of the alluvial fans produce three times more runoff and four to five times more sediments respectively than the lower parts of the alluvial fans sectors. In more homogeneous hillslopes covered with colluvium (Sanchez, 1995) (Table 6) differences in sediment yield between hillslope sectors were not significant, but were five to six times higher on the southern exposure than on the northern exposure. In the case of runoff, differences between exposures are less marked, but on the south-facing hillslope, the upper sector functions as a source for the lower sector. In the latter, the annual runoff coefficient drops to one third of the value on the upperslope.

At the storm event scale, runoff and sediment yield values from the bounded plots along the catena reflect the variability of local conditions when plotted against rainfall (Fig. 16). However, their envelopes show that the largest records do not occur at the greatest, but at intermediate rainfall volumes. In

Table 6
Runoff coefficient and sediment yield (± 1 SE) in the three vegetation types of the Rambla Honda catena, and in two *Stipa*-covered hillslopes of different exposure

		Slope length (m)	Runoff coefficient (%)	Sediment yield (g m^{-2})
Bounded plots	Lower Fan Sector *Retama* sp.	10	2.06 ± 1.55	6.08 ± 1.30
	Upper fan sector *Anthyllis* sp.	10	5.76 ± 1.65	22.38 ± 12.90
	Upper hillslope sector *Stipa* sp.	10	5.64 ± 1.43	34.41 ± 14.87
Hillslope sectors (colluvium-covered)	North aspect	17	5.2	23
	North aspect	60	4.3	19
	South aspect	23	7.5	128
	South aspect	49	1.8	111

Study period: 1 Sept.–91 to 31 Aug.–92. Source: (Puigdefabregas et al., 1996; Sanchez, 1995).

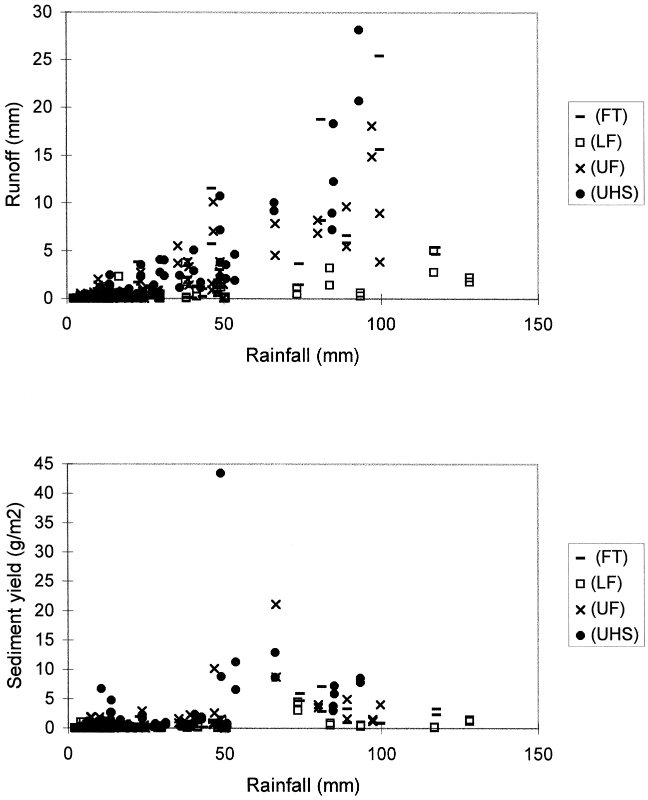

Fig. 16. Runoff (R) (*top*) and sediment yield (SY) (*bottom*) vs. rainfall at the plot scale in the Rambla Honda catena. Rainfall event scale values for the period 1, Sept. 1991–31 Aug. 1997. FT = Fan/fluvial terrace; LF (Lower fan); UF = Upper fan; UHS = Upper hillslope.

the case of runoff, this feature may be explained because large events are also more discontinuous in time, which increases the opportunities for infiltration. The decline of sediment yield at large rainfall events reflects the temporal exhaustion of sediments. The upper hillslope and the fan-terrace sectors behave as the main runoff sources, while the upper hillslope and fan-heads function as the main sediment sources.

The spatial location of runoff sources in the upper hillslope sectors, which are steeper and less permeable than the footslope sedimentary fill, agrees with the results reported from Sde Boqer, in Israel (Yair and Lavee, 1985), but are in contrast with those obtained at Walnut Gulch, in Arizona (Abrahams et al., 1988), where upper hillslopes supported higher infiltration rates.

As reported from other arid regions, such as in Sde Boqer, Israel (Yair and Lavee, 1985; Abrahams et al., 1988), and Walnut Gulch, Arizona (Yair and Lavee, 1985; Abrahams et al., 1988), in Rambla Honda, runoff sources are associated with low infiltration rates (Fig. 7) and fine-textured soils (Table 1) such as occur on the upper hillslope and the fan-terrace sectors. Sediment sources are found in steeper and fine-textured soils, where both the sediment availability and transport capacity are greater. At the scale of individual hillslope elements, these conditions are found on rocky hillslopes and fan-heads. At the landscape level, the main sediment sources are found on hillslopes with southern exposures.

4.2. Redistribution of water and sediments

4.2.1. The spatial distribution of soil moisture

The spatial patterns of soil moisture content convey information about the efficiency of water redistribution processes. Where water movement is largely driven by gravity, we may expect to find significant relationships between soil moisture and topography. On the other hand, the lack of association between soil moisture and relief can be considered as evidence that local factors override gravity in controlling the spatial distribution of water.

In Rambla Honda seasonal averages of soil moisture, calculated from a three year record, do not steadily increase downslope (Fig. 17). In winter and autumn, minimum values are found halfway the slope, particularly in the uppermost soil layer. In spring and summer, soil moisture decreases downhill. Winter and autumn soil moisture contents lie between 4% and 20%, which is far below saturation (i.e., 21%–32%), but within the range of field capacity (i.e., 12%–20%), as shown in Table 7. These are therefore the only seasons in which soil moisture could exceed field capacity and could move downslope driven by gravity. Saturated conditions, are likely to be of extremely short duration.

The association between soil moisture content and topography has been examined at the seasonal resolution, using topographic attributes that describe the influence of terrain on the downslope flow of water or sediments (Puigdefabregas et al., 1998). The terrain attributes have been derived from a digital elevation model with 1 m spatial resolution using PCRaster software (Karssenberg, 1996; Wesseling et al., 1996). The computed terrain attributes were Local Slope Angle (SLO), Specific Catchment Area (ARE), Wetness Index (ATB = ln (ARE/tan SLO)),

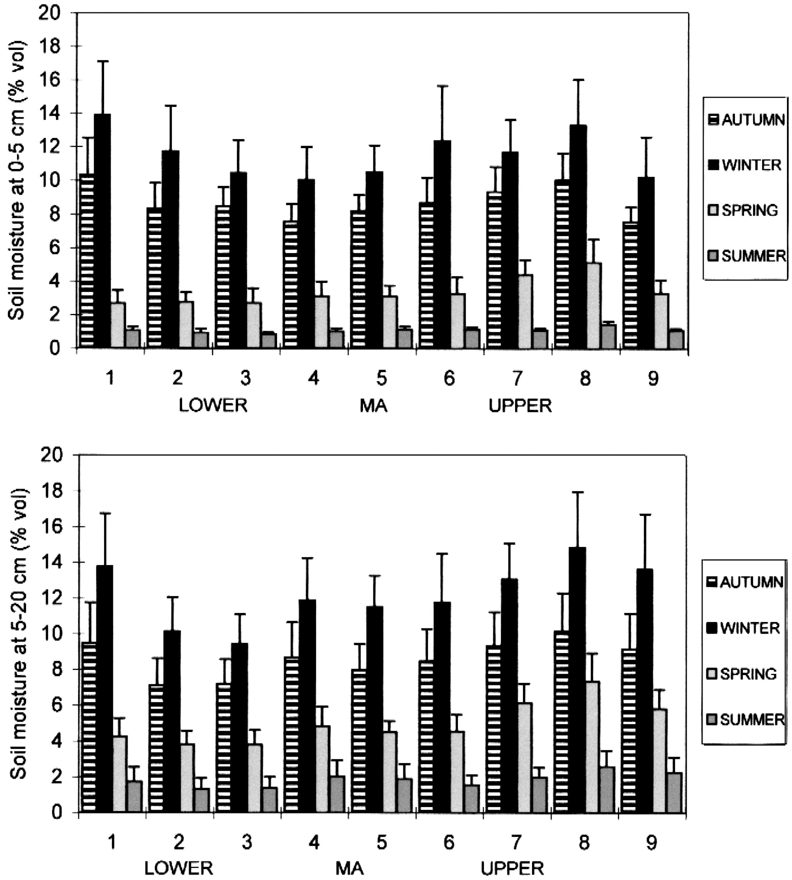

Fig. 17. Seasonal averages (±1 SE) of soil moisture distribution along the Rambla Honda catena for the period Sept. 91 to Aug. 94, in the surface (top) and subsurface (bottom) soil layers. MA1 = Alluvial Fan/Fluvial terrace; MA2-MA3 = Lower alluvial fan; MA4-MA6 = Upper alluvial fan; MA17-MA19 = Upper hillslope. Source: (Puigdefabregas et al., 1998).

Table 7
Physical soil properties (mean values ± 1 SE) in intershrub areas at both the upper hillslope (MA8) and the lower sector of the alluvial fan (MA2)

	Soil layer (cm)	Upper hillslope MA18	Lower hillslope MA12
Slope gradient (°)		20 ± 2	5 ± 0.5
Soil depth (m)		< 0.5	5
Bulk density whole soil (kg L^{-1})	0–5	1.8 ± 0.06	2.1 ± 0.15
	5–20	1.9 ± 0.14	2.0 ± 0.12
Total porosity (L^{-1})	0–5	32 ± 1.5	20.7 ± 0.9
	5–20	28 ± 1.4	24.5 ± 1.6
Porosity fine earth (L^{-1})	0–5	0.55 ± 0.02	0.47 ± 0.03
	5–20	0.54 ± 0.01	0.40 ± 0.01
Total extractable water (L^{-1} at 0.03 MPa)	0–5	0.20 ± 0.009	0.12 ± 0.01
	5–20	0.17 ± 0.01	0.14 ± 0.01
Extractable water fine earth (L^{-1} at 0.03 MPa)	0–5	0.38 ± 0.015	0.33 ± 0.016
	5–20	0.36 ± 0.012	0.25 ± 0.01
K_{sat} (m/day)	0–5	1.01 ± 0.44	1.72 ± 0.42
	5–20	0.57 ± 0.1	1.37 ± 0.51
Infiltration (mm/h)		8 ± 0.6	40.5 ± 2.1

K_{sat}: saturated hydraulic conductivity. Source: (Puigdefabregas et al., 1998).

and Length Slope Factor ($LSF = (ARE/22.13)^n (\sin SLO/0.0896)^m$), where n and m are constants, 0.4 and 1.3 respectively (for a review of the application of terrain attributes see Moore et al., 1991). In order to remove local effects, partial correlation coefficients between soil moisture and topographic indices were calculated, holding soil field capacity constant.

Soil moisture content was found to be most significantly associated with LSF and ln(ARE) (Table 8).

Table 8
Partial correlation coefficients between mean soil moisture and topographic variables, holding constant field capacity, in the Rambla Honda hillslope

	Rainfall (mm)	0 cm–5 cm soil layer				5 cm–20 cm soil layer			
Season		SLO.fcd	LARE.fcs	ATB.fcs	LSF.fcd	SLO.fcd	LARE.fcs	ATB.fcs	LSF.fcd
Autumn-91	56	0.29	0.4	0.45	0.42	*0.71*	0.43	−0.08	*0.75*
Autumn-92	70	0.16	0.09	0.22	0.57	0.27	0.54	0	0.4
Autumn-93	45	−0.12	0.38	−0.06	0.63	0.08	0.38	−0.33	0.65
Autumn-94	139	−0.12	0.61	*0.71*	**0.88**	0.14	*0.71*	−0.11	**0.8**
Winter-92	162	0.19	0.18	0.12	0.63	0.12	*0.79*	0.15	*0.76*
Winter-93	121	0.04	0.27	0.42	0.67	0.19	0.53	−0.09	0.38
Winter-94	53	−0.06	0.62	0.5	*0.75*	0.19	0.64	−0.08	*0.71*
Spring-92	87	0.49	0.03	−0.5	0.44	0.24	0.33	−0.32	0.45
Spring-93	55	−0.03	0.41	−0.19	*0.72*	0.24	0.15	−0.53	*0.74*
Spring-94	23	0.45	0.07	−0.49	0.55	0.43	0.3	−0.42	0.41
Summer-92	17	0.27	0.48	0.24	0.19	0.08	0.68	0.06	0
Summer-93	55	0.5	0.49	−0.04	0.49	0.44	0.28	−0.45	0.61
Summer-94	23	0.66	0.18	−0.55	*0.76*	0.45	0.2	−0.52	0.59

Study period: Oct. 91–Dec. 94; SLO: slope angle; LARE: ln (ARE), where ARE is the specific catchment area; ATB: wetness index; LSF: length slope factor: fcs: field capacity at the 0 cm–5 cm upper soil layer; fcd: field capacity at the 5 cm–20 cm soil layer. Bold: $p < 0.01$; italics underlined: $p < 0.05$. Source: (Puigdefabregas et al., 1998).

Significant correlations are constrained to the humid periods of the year, and even then, they were recorded only in 5 of the 13 seasons included in the reference period. The highest correlation coefficient was recorded in autumn 1994, which was particularly rainy (139 mm).

These findings suggest that gravity-driven transfer of water between hillslope elements does not occur frequently but may be significant under particularly humid conditions. During the rest of the time, local factors, such as pore volume, rock fragment cover or grain size, are more important in determining the spatial distribution of soil moisture content than lateral transfer processes. For example, the relatively high silt and clay content of the soils in the upperslope cause moisture contents there to remain higher during the dry seasons than in the lower hillslope section (Table 1) where the soils are much more sandy.

This assumption is consistent with the effective runoff length that can be roughly estimated by plotting the annual runoff coefficients against slope length. The data were obtained in several studies carried out simultaneously in runoff plots and hillslope sections of several lengths during the period 1 October 1991–30 September 1992 at Rambla Honda (Puigdefabregas and Sanchez, 1996). As expected, runoff coefficients decrease dramatically with slope length up to 10 m–15 m, and remain very low ($< 4\%$) at greater slope lengths. The relationship can be described by a potential curve $y = a\ x^b$, where $y =$ annual runoff coefficient, $x =$ slope length (m), $a = 33.38$, $b = -0.780$, $r = -0.78$. This means that when considering hillslope sectors longer than 10 m–15 m, most of the rainfall infiltrates and evaporates on the spot, and a very small proportion is left for downhill transfer, which is likely to occur only during extreme rainfall events.

However, it should be remembered that in those rare events redistribution over substantial distances occurs mostly because water and sediments are conveyed through first order channels that often connect upper hillslopes with their footslope sedimentary fill. The understanding of this process in arid climates requires information on how water and sediments are delivered to first order channels. To this purpose synchronic and high time resolution information of within-event soil moisture, inter-channel runoff and channel discharge is essential. Some approaches in this direction were initiated in Rambla Honda, taking advantage of the existing soil moisture sensors, runoff plots and stream gauging installations in the field (Puigdefabregas et al., 1998).

4.2.2. Redistribution of water and sediments through first order channels

The autumn rains that occurred from 29.09.94 to 04.11.94, after the dry summer months, were studied in detail. The total rainfall collected during the whole period was 150 mm and was distributed over three major events of 50 mm, 66 mm and 30 mm respectively.

The second rainfall event is interesting because it occurred over moist soil, with about 10% of water content (Fig. 18). The event consisted of two subevents of 42 mm and 24 mm, separated by a dry period of 12 h. Focusing on the first subevent we can follow the responses of the upper hillslope (MA8) and the fan (MA2) sectors in terms of soil moisture and runoff. The rain lasted for 3.5 h, and its mean intensity was 12 mm h^{-1} but it was also interrupted by a period of 1 h in which rainfall was lighter. Rainfall in each of the two parts of the subevent was 22 mm and 18 mm respectively.

In the upper hillslope (Fig. 18 MA8) the water content of the surface soil layer rose quickly from the start of the rain, during the first part of the subevent. The subsurface layer response was delayed by about one hour, but then also rose very fast and exceeded the soil moisture content of the surface layer. In this way, in the subsurface layer, a soil moisture plateau of around 45% was built up and lasted for 4 h, 2 h after the rain ceased. Such a water content can be considered very close to saturation, given the soil pore volume for the area, which is around 30% for the whole soil and 55% for the fine earth (Table 7). The overland flow hydrograph at the runoff plot develops in parallel to rainfall and soil moisture dynamics. The rainfall in the second part of the subevent caused a peak of soil moisture in the surface layer and a burst of water discharge in the channel.

Runoff coefficients for the first part of the subevent were 45% in the runoff plot, but negligible in the channel. For the second part of the subevent, runoff coefficients were 40% in the runoff plot, 5%

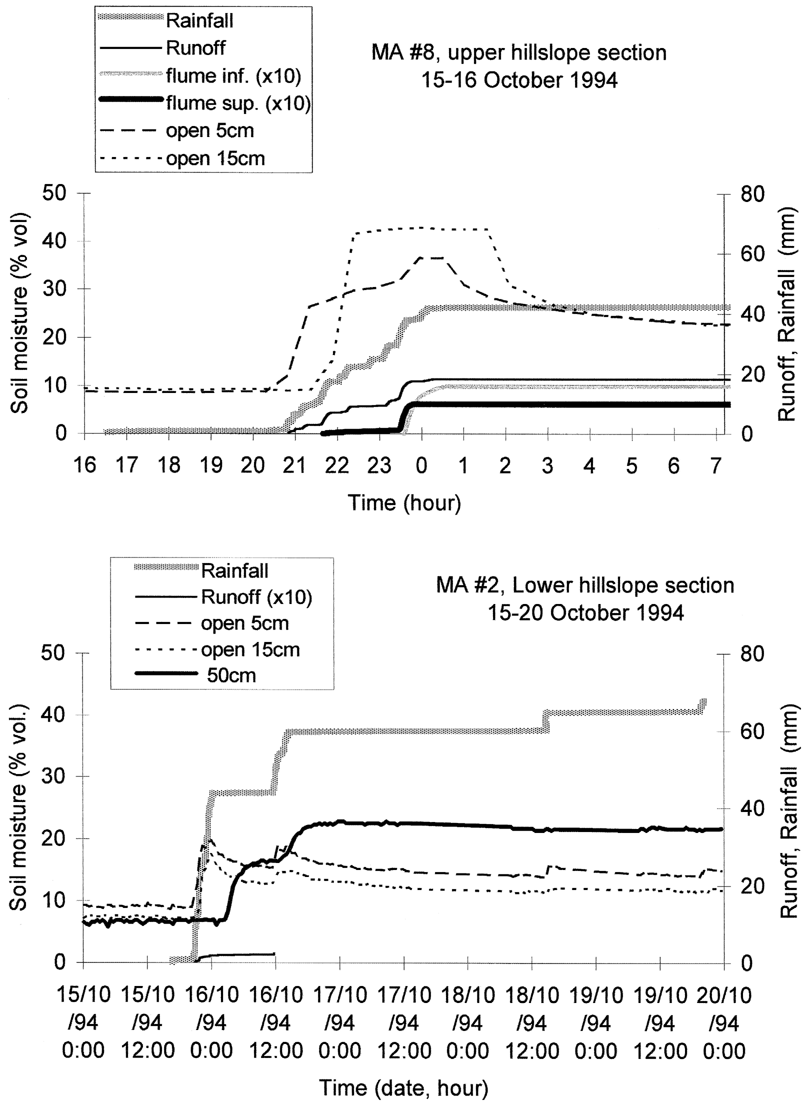

Fig. 18. Cumulative time evolution of rainfall, runoff and soil moisture, in bare ground areas, at 5 cm and 15 cm depth, during the rainfall event of 15–16 September, 1994, at the hillslope sector (MA8) and the lower fan sector (MA2) of Rambla Honda. Source: (Puigdefabregas et al., 1998).

in the upper part of the channel (F3) and 8% in the lower reach of the channel (F1). The larger runoff coefficient in the lower flume is explained by the inputs from areas with exposed bedrock, near the channel in the section between the two flumes.

In the fan sector (Fig. 18, MA2), the soil moisture content of the surface and subsurface layers also reacted quickly to the rain, but remained far below saturation because the water was drained to deep layers. The deepest soil layer in which water content was measured (−50 cm) delayed its response by about 5 h during the first subevent, but only 2 h in the second, probably because water conductivity of the topsoil had increased meanwhile. The soil moisture content at −50 cm exceeded that of the upper soil layers and reached a level of 22% that lasted for several days. Considering the soil porosity for the area (Table 7), at such moisture contents the soil is generally above the field capacity, and close to saturation. Locally, however, the soil may be nearly saturated. Overland flow at the runoff plot initiated as the rain started but was short lived (2 h) and resulted in a runoff coefficient far below that of the upper hillslope ($< 1\%$).

During this event the borehole installed in the channel upstream of the lower flume (F1), recorded a sudden build up of a saturated zone up to 4.5 m above the bedrock, that quickly declined and disappeared 20 days later. No evidence of water was observed in the other three boreholes installed in the field site, despite the fact that two of them were located in the main Rambla Honda channel, which was filled with flood water for several hours.

The analysis of hillslope responses to this complex rainfall event allows the identification of two mechanisms of overland flow generation. The first involves the saturation of the uppermost soil layer which occurs just after rainfall initiation. It is short lived because it disappears as soon as the progress of the wetting front develops a transmission zone that allows for the drainage of the upper soil layer. This kind of response is spatially heterogeneous, because it requires a pulse of high rainfall intensity and specific micro-site conditions, such as high soil sorptivity and the lack of a fully developed washing-in layer. These conditions are likely to be met in the litter-rich patches associated to the tussocks (Section 3.1.2). The second mechanism requires the persistence of nearly saturated condition in a shallow subsurface soil layer. It may occur in areas where permeability decreases with soil depth, and leads to a very reactive condition in which a small additional amount of rainfall may produce large scale runoff.

The time distribution of rainfall over time is often discontinuous, particularly in arid climates. During the described event, for example, rainfall bursts and pauses lasted around 10 to 15 min (Fig. 18, MA8). Once the uppermost soil layer has been saturated, overland flow can occur over distances that can be covered within the time of the rainfall burst. During pauses in rainfall, the top soil layer drains out and overland flow infiltrates. Thus, the duration of rainfall bursts and pauses, rainfall intensities, drainage rates of the upper soil layer and surface roughness, constrain maximum overland flow length. Spatial heterogeneity of the soil surface and of rainfall intensity patterns at the scale of the hillslope section, desynchronise the redistribution process across space. Furthermore, unless rainfall intensity exceeds the infiltration rate of the soil surface, when rainfall resumes, the top soil layer must be filled first with water before producing overland flow again. Both features lead to substantial reductions of actual overland flow distances.

The reactive condition which is set by the second mechanism of overland flow generation described above provides a long lasting saturation of the subsurface soil layer. In this way, the effect of rainfall variability on the water content of the uppermost layer tends to be buffered, allowing overland flow to last for longer periods of time and to cover greater distances. Therefore, this mechanism is probably the most important for the creation of hydrological connections across hillslopes. However, the distances involved are likely to be short where the soil moisture content of the subsurface layer falls quickly after rain ceases. In this hillslope sector, the saturated condition lasted 2 h after rainfall interrupted, and 24 h later, the water content was below field capacity (Fig. 18 MA8). Only if rainfall is frequent and the evapotranspiration is low, as may occur in winter, this mechanism could be seasonally relevant at the hillslope scale.

Where soils are shallow or have less permeable layers at shallow depth, as in the upper hillslope sector, this way of overland flow generation requires smaller rainfall amounts and hence, is likely to occur more frequently. In deep and permeable soils, such as those in the fan sector, this mechanism occurs at much lower frequencies because it requires large and long-lasting rainfall events. However, once they are formed the reactive conditions are more persistent, and are likely to produce runoff even with moderate rainfall amounts.

An indirect support to the idea of short average runoff distances, probably less than 10 m, is provided by this event (Fig. 18 MA8). The rainfall during the reactive phase was about 20 mm and produced 8 mm of runoff in the runoff plot (2 m $\times$ 10 m). Similar specific runoff amounts from the area situated at less than 10 m from the stream course draining to the upper flume (i.e., 437 m^2,) (Puigdefabregas et al., 1998) would produce a total channel discharge of 3.5 m^3 which is well above the recorded discharge (2.6 m^3).

The development of the soil moisture content at −50 cm depth in the fan, during the rainfall event (Fig. 18 MA2), suggests that groundwater recharge within the sediment fill of the valley bottom occurs mainly by percolation. The fan is built up of alternating and discontinuous layers of different grain size and permeability (Puigdefabregas et al., 1996). As happens in our record, the soil moisture content above the uppermost less permeable layer may temporary exceed field capacity. Water is then constrained to flow laterally and is gravity-driven over this layer until it is interrupted. Then the percolating water percolates further and eventually the process is repeated above the next less permeable layer. This stair-like flow process does not require saturation and can explain how water reaches the deepest layers of the sediment body and is made available to deep rooted plants as *Retama* (Haase et al., 1996b).

The fact that the only borehole that reacted to the rain was located in a first order channel that drains the hillslope, and the sudden and ephemeral nature of the built up saturated water body, discards any possibility of recharge through continuous subsurface flow or percolation. Channel infiltration is the most likely input as supported by field observation during the event. Upstream of the borehole, there is a coarse gravel reach in the channel, where part of the flowing water infiltrates.

4.2.3. Inter-channel and channel contribution to water and sediment redistribution across hillslopes

In spite of the large differences of runoff and sediment yield that are found across hillslopes at the plot scale, the ranges of water and sediment redistribution within inter-channel areas are limited because of the short runoff lengths that are usually involved. In contrast, fluxes along first order channels are mainly responsible for long distance redistribution between hillslope sectors.

Concerning water, first order channels connect upper hillslope sectors with their foot slope sedimentary fill, particularly when the time structure of rainfall allows for significant runoff yields. However, even in such conditions, near-channel areas are probably the main sources of water, and channel contribution to water recharge of the sediment fill is limited. This is particularly true in cases such as Rambla Honda, where hillslope areas are small compared to the volume of relatively permeable sediments at the valley bottom. In this situation, the saturated wedges that occasionally develop at the outlet of the first order channels draining hillslope areas, tend to dissipate within the sediment fill of the valley bottom.

Concerning sediments, channels are again the main redistribution structures. They are also the main sources when they cut into sedimentary bodies and the sediment supply from the upper hillslope sectors is limited by weathering rates. Again this is the case of Rambla Honda, as shown by the rainfall event studied (Table 9). The upper hillslope sector delivered 2.47 g m^{-2} of sediments at the plot scale, and 2 g m^{-2} at the catchment scale (flume #3). This means a sediment delivery ratio of 0.8, which agrees with the transient characteristic of the debris mantle in such slopes. Sediment yield where the channel cuts into the foot slope alluvial fan (flume #1), increased to 4 g m^{-2}, while at the plot scale, inter-channel areas of the fan delivered only 0.22 g m^{-2}

Table 9
Runoff and sediment yield from runoff plots (2 m × 10 m) (±1 SE) and flumes in the studied hillslope, at Rambla Honda, during the rainfall event no. 62 (15–16, October, 1994) with a total rainfall of 66 mm

		Runoff coefficient (%)	Sediment yield (g m^{-2})		
			Total	> 1 mm	< 1 mm
Plots (2 m × 10 m)	Upper hillslope	19.10 ± 2.3	2.47 ± 1.01		
	Upper fan sector	8.50 ± 4.12	1.31 ± 1.01		
	Lower fan sector	0.46 ± 0.20	0.22 ± 0.07		
	Fan/fluvial terrace	6.98 ± 0.43	0.76 ± 0.53		
Flumes	Upper (F3) (0.29 ha)	1.40	1.95	1.58	0.37
	Lower (F1) (4.65 ha)	2.63	4.02	0.37	3.65

of sediments, one order of magnitude less than the upper hillslope.

Such an increase in sediment yield from the catchment outlet, at the hillslope base, can only be explained by the fact that the fan is presently being cut into. The channel itself becomes a more effective source of removable sediments than the inter-channel areas, where gravel armouring is widespread and runoff energy is less. In Rambla Honda, these washed out sediments are mostly fine and are redeposited downstream, in the same fan system.

On the upper hillslope sector, with a gradient of 28°, 81% of the channel sediment discharge was bedload (Ø > 1 mm), while at the footslope, with a gradient of 7°, this proportion decreased to 9%. At the slope break joining the two hillslope sectors, coarse sediments are deposited and fine materials are washed out. In this way, a channel reach with high infiltration capacity develops and becomes a site of water recharge to the sediment fill in the valley bottom.

5. Concluding remarks

The densities and spatial patterns of infiltration and depositional sites are factors that determine the spatial distribution of driving forces and resistances to the fluxes of matter, and hence, the lengths at which water and sediment are redistributed across hillslopes. These factors may work at different time scales. Topography (Yair and Klein, 1973; Poesen, 1984; Yair and Lavee, 1985; Abrahams and Parsons, 1991a) and rock fragment distribution (Abrahams and Parsons, 1991b; Poesen et al., 1994) often operate at the long term and can be considered as rather constant boundary conditions, which are in most cases, the product of driving forces that are not active at present. In contrast, vegetation works over the short term (Abrahams et al., 1995) in a dynamic and interactive way with runoff and sediment movement.

Results from Rambla Honda point at the role of vegetation as a source of spatial heterogeneity. Dryland vegetation is often sparse, and the formation of plant clumps triggers a number of feedback mechanisms that contribute to significant differences in soil properties between the clump and the bare patches. Runoff and sediment trapping, as well as mutual facilitation between functional plant types, are important aspects of this nucleation processes by increasing surface roughness and spatial contrasts in terms of soil fertility and soil hydraulic properties. These spatial mosaics are not static, but may change their replacement rate, their shapes and arrangement in space through their interaction with runoff and sediment movement.

The detailed analysis of water redistribution presented in Section 4.2.2 suggests that the temporal and spatial scales of runoff generation are controlled by the combined effect of the temporal variability of rainfall events and the structure of the soil. The two mechanisms observed here, near surface and subsurface saturation, point to two distinct conditions of persistence and spatial continuity, and interestingly, one of them allows for some variation in the spatial range of hydrological connections between hillslope elements. From here, it is self-evident that a given climate will cause a particular pattern of runoff lengths.

Field evidence of a probable relationship between runoff length and the spatial structure of the discontinuous mosaic of vegetation cover have been presented in several sections of this paper. If such a relationship exists indeed, it may be hypothesised that, given a topography, soil structure and sediment availability conditions, the seasonal patterns of runoff lengths are reflected in the spatial arrangement of vegetation patches. This is true for a certain range of rainfall regimes and plant growth rates, in which vegetation mosaics can be organised in a way that maximises runoff harvest and the resistance to sediment movement. Conversely, on the hillslopes where the fluxes of water and sediments exceed the adjustment capacity of the vegetation, redistribution lengths increase, and the spatial arrangement of plant patches loses its interactive character and becomes relict, being locally affected by differential erosion.

This simple rationale may provide insight in the assessment of the land condition under arid environmental conditions. A vegetation mosaic will be stable as long as the spatial organisation of plant clumps is compatible with the runoff lengths that result from a given climate pattern. Individual or grouped disturbances in such a vegetation pattern will create asynchronies between lateral water transfers and runoff harvesting structures, pushing the mosaic beyond certain, possibly irreversible, thresholds. The adjustment to the new situation may operate as a switch, leading either to an increase or a decrease of the ''grain-size'' of the mosaic. A successful adjustment could consist of a replacement of the plant community by another one that can establish a new equilibrium with new runoff lengths. The replacement of grasses by shrubs, which has been observed in many arid rangelands around the world (Schlesinger et al., 1990; Schlesinger, 1996; Koppel van de et al., 1997) as a response to disturbances that increase runoff lengths, could probably be considered as examples of this trend. On the other hand, if the vegetation fails to make the adjustment the mosaic could decay by increasing differential erosion between bare and vegetated patches. Those apparently opposite responses do not have to be dramatically different, often only the scale of relationships will show subtle but unambiguous differences.

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